Searching for parton saturation at FCC-eh, LHeC and EIC

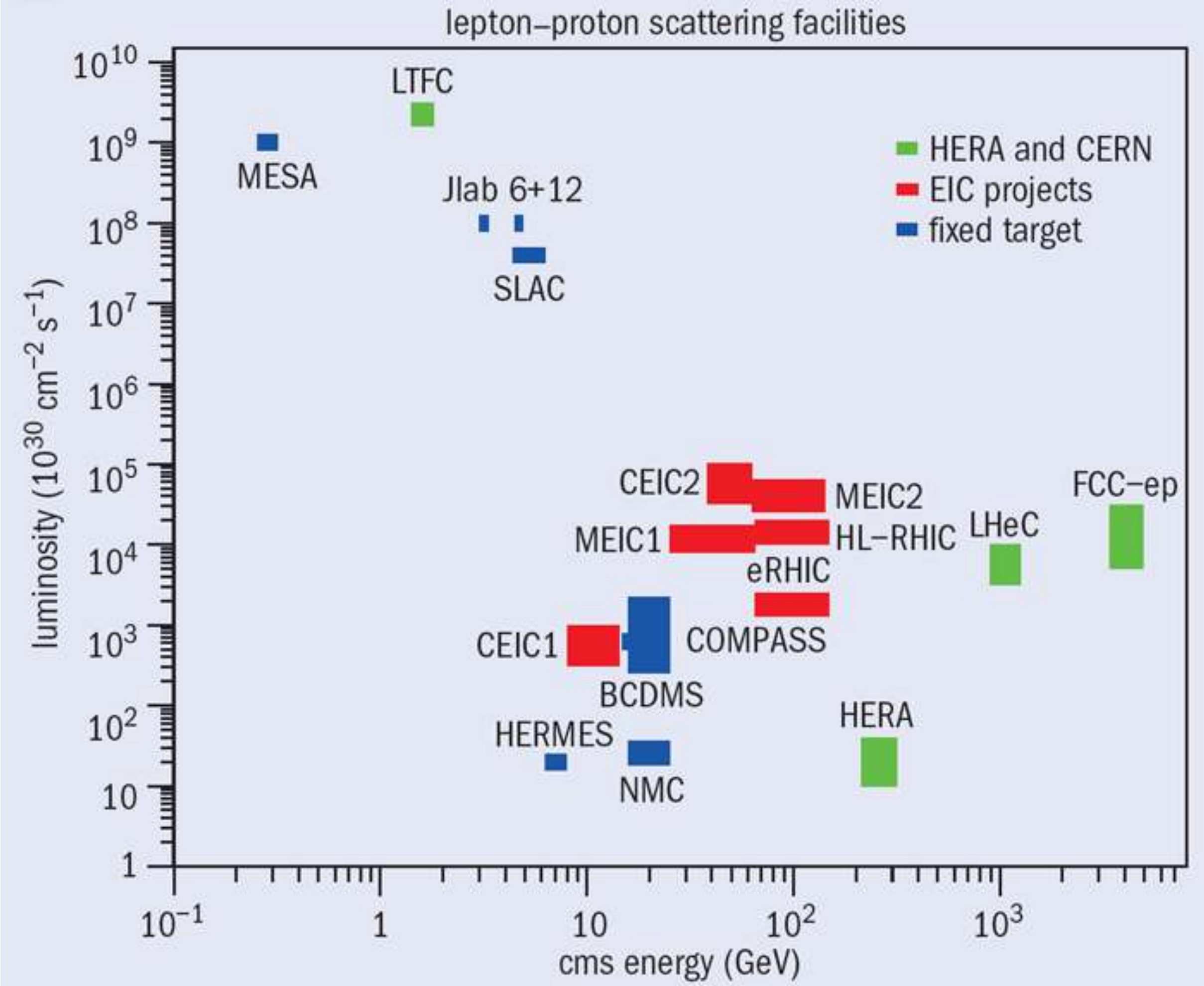
Open questions and path forward

Anna Staśto

PennState
Eberly College of Science

Snowmass Energy Frontier Workshop, July 21, 2020

Past, present and future of DIS



US EIC

energy $\sqrt{s} \simeq 20 - 140 \text{ GeV}$

luminosity $10^{34} \text{ cm}^{-2}\text{s}^{-1}$

wide range of nuclei: p,d,^{3}He,^{4}He,C,Ca,Cu,Au

polarization of electron and nucleon beams

LHeC /FCC-ep (CERN)

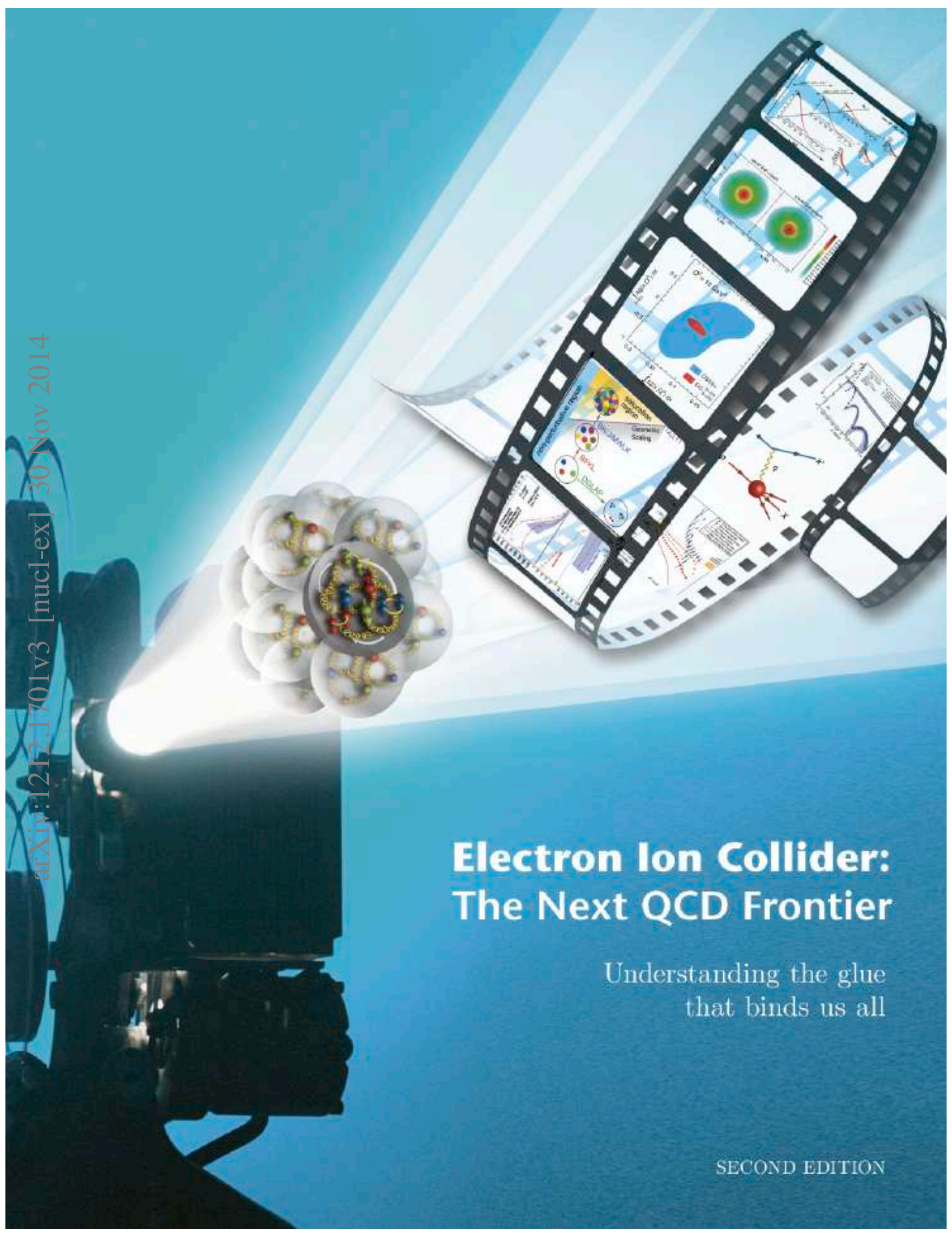
energy $\sqrt{s} \simeq 1 - 5 \text{ TeV}$

luminosity $10^{34} \text{ cm}^{-2}\text{s}^{-1}$

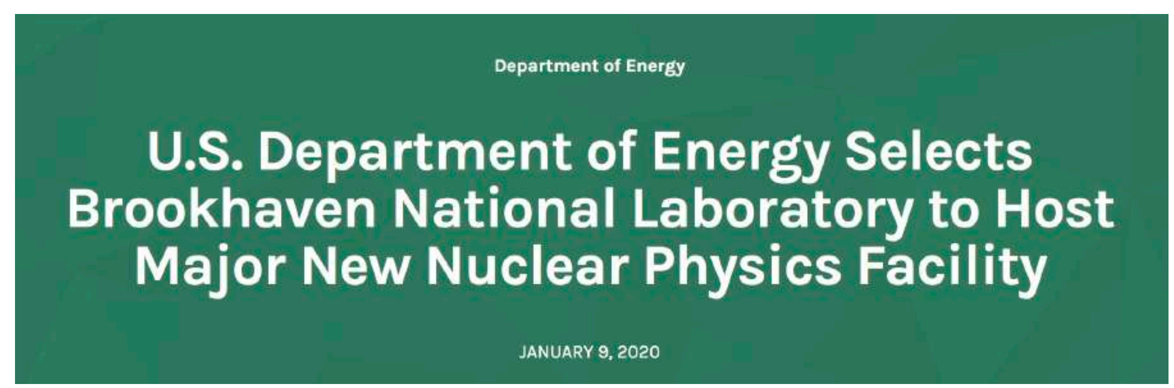
electron proton/ion: p,Pb

Physics at high densities at the EIC

2012: EIC White Paper



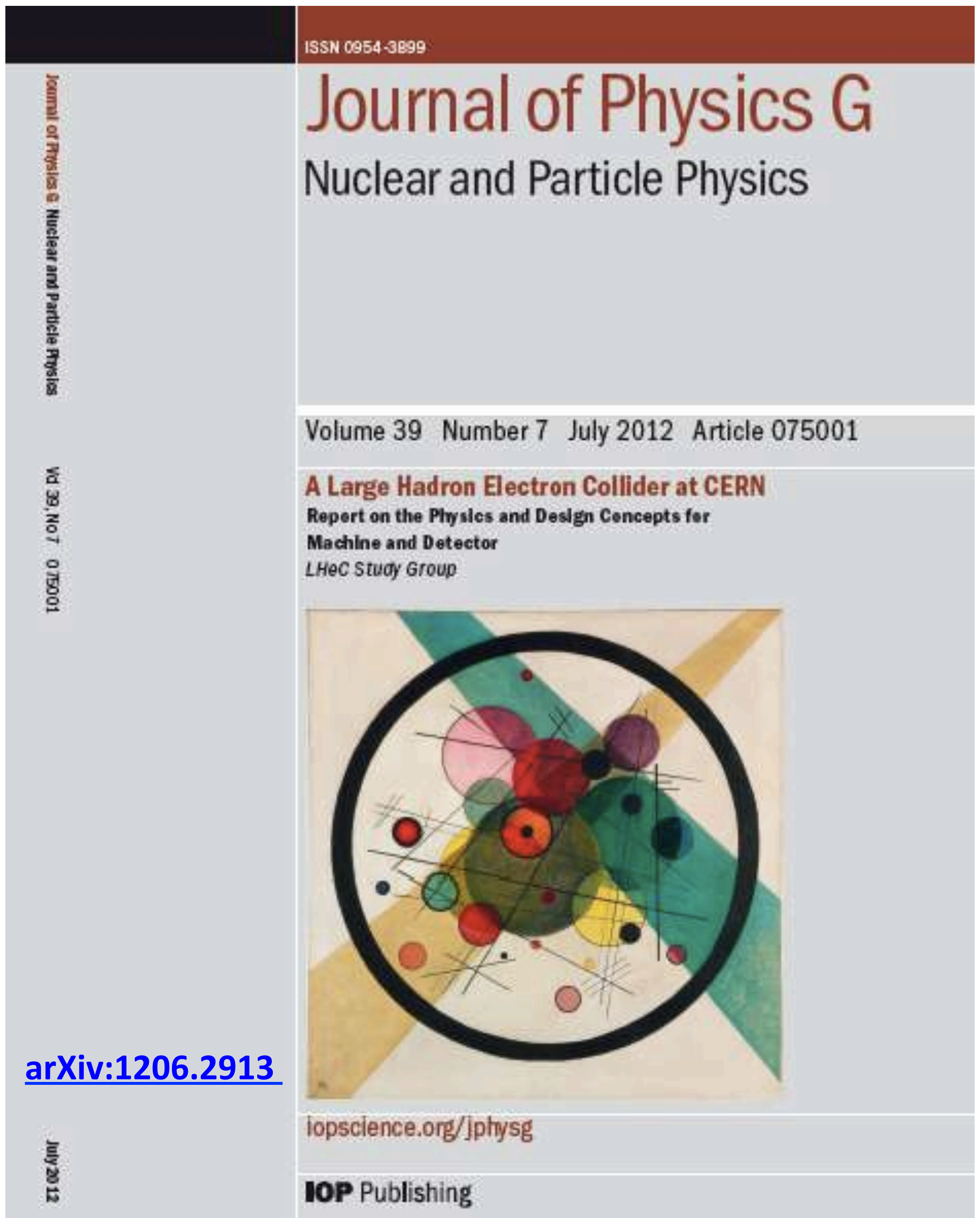
Chapter on high gluon density in QCD



2020/2021 Effort towards the Yellow Report: Physics/Detector development.

Physics at high densities at the LHeC

2012: LHeC Conceptual Design Study

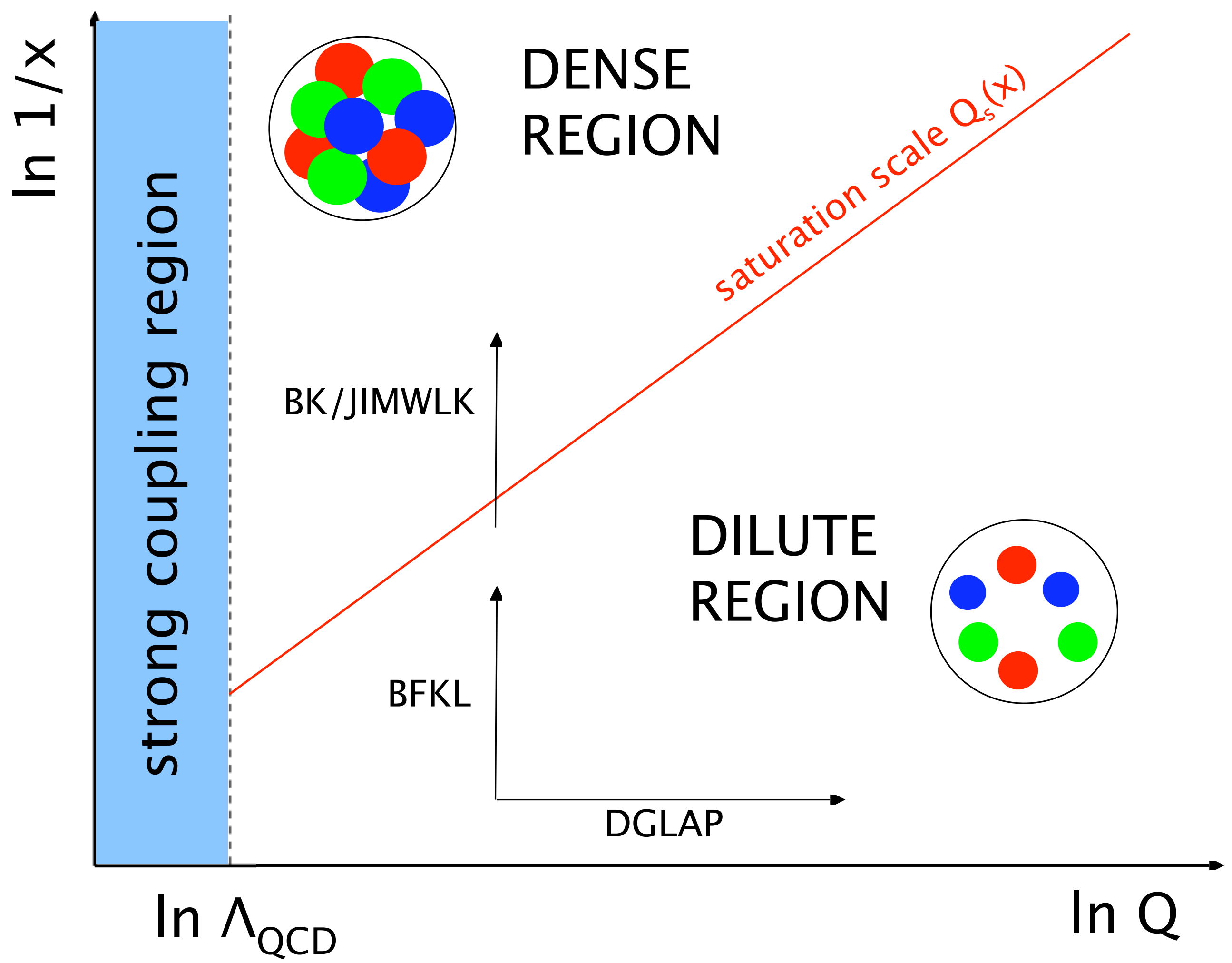


arXiv:1206.2913

LHeC: Large Hadron electron Collider. CERN Project to collide electrons with LHC proton/ion beam

2020 update of the CDR to be released soon (July 2020)

Transition regime to high parton density



x and A dependent saturation scale.

$$\frac{A \times xg(x, Q_s^2)}{\pi A^{2/3}} \times \frac{\alpha_s(Q_s^2)}{Q_s^2} \sim 1$$

$$Q_s^2 \sim A^{1/3} Q_0^2 \left(\frac{1}{x}\right)^{\lambda}$$

Saturation boundary needs to be determined by experiment

HERA data consistent with very low Qs
Partonic/perturbative interpretation uncertain

$$Q_s^2 \leq 1 \text{ GeV}^2$$

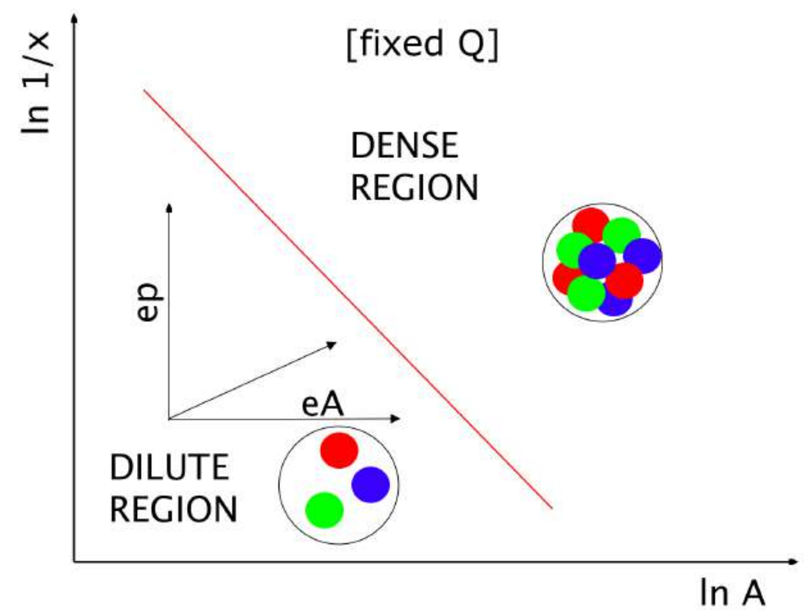
Gluon density can increase by: decreasing x and/or increasing A

Strategy for making target more 'black'

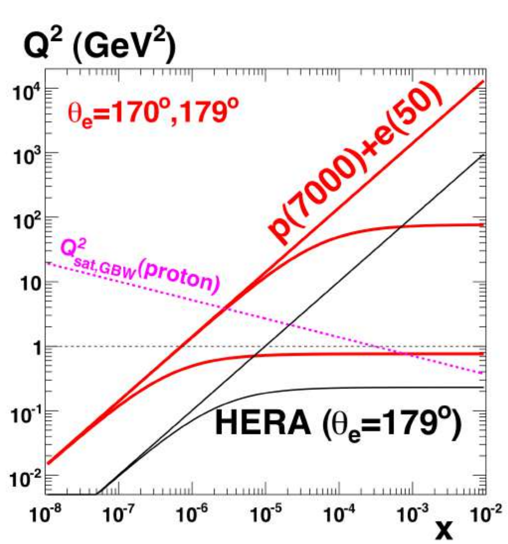
Saturation scale: $Q_s^2 \sim A^{1/3} Q_0^2 \left(\frac{1}{x}\right)^{\lambda}$

Two-pronged approach

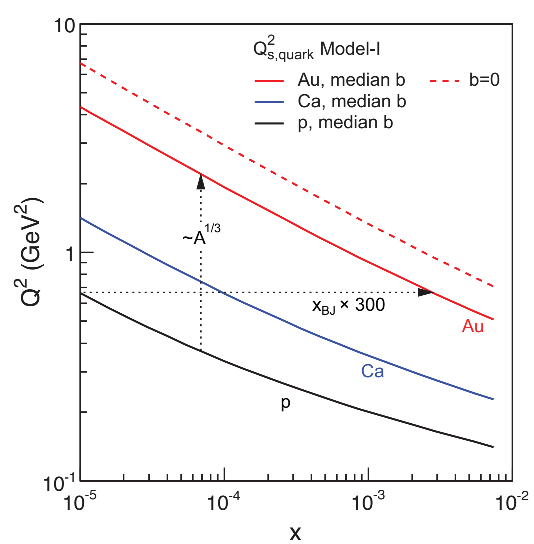
Probing lower x in ep.
Evolution of a single source



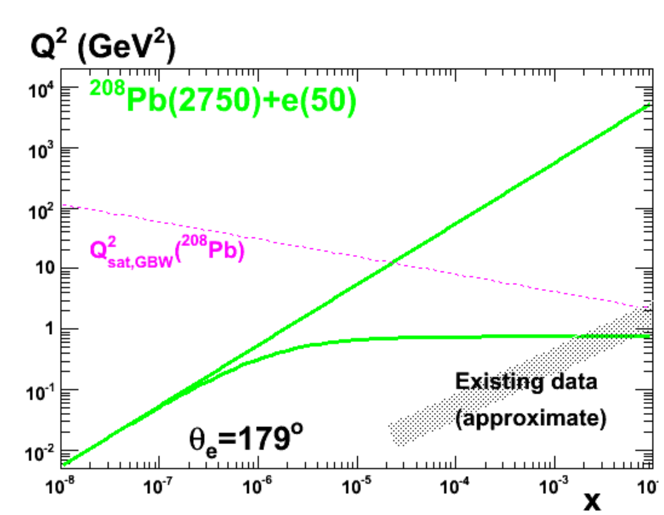
eA scattering
Many sources overlapping in impact parameter .



LHeC/FCC-ep

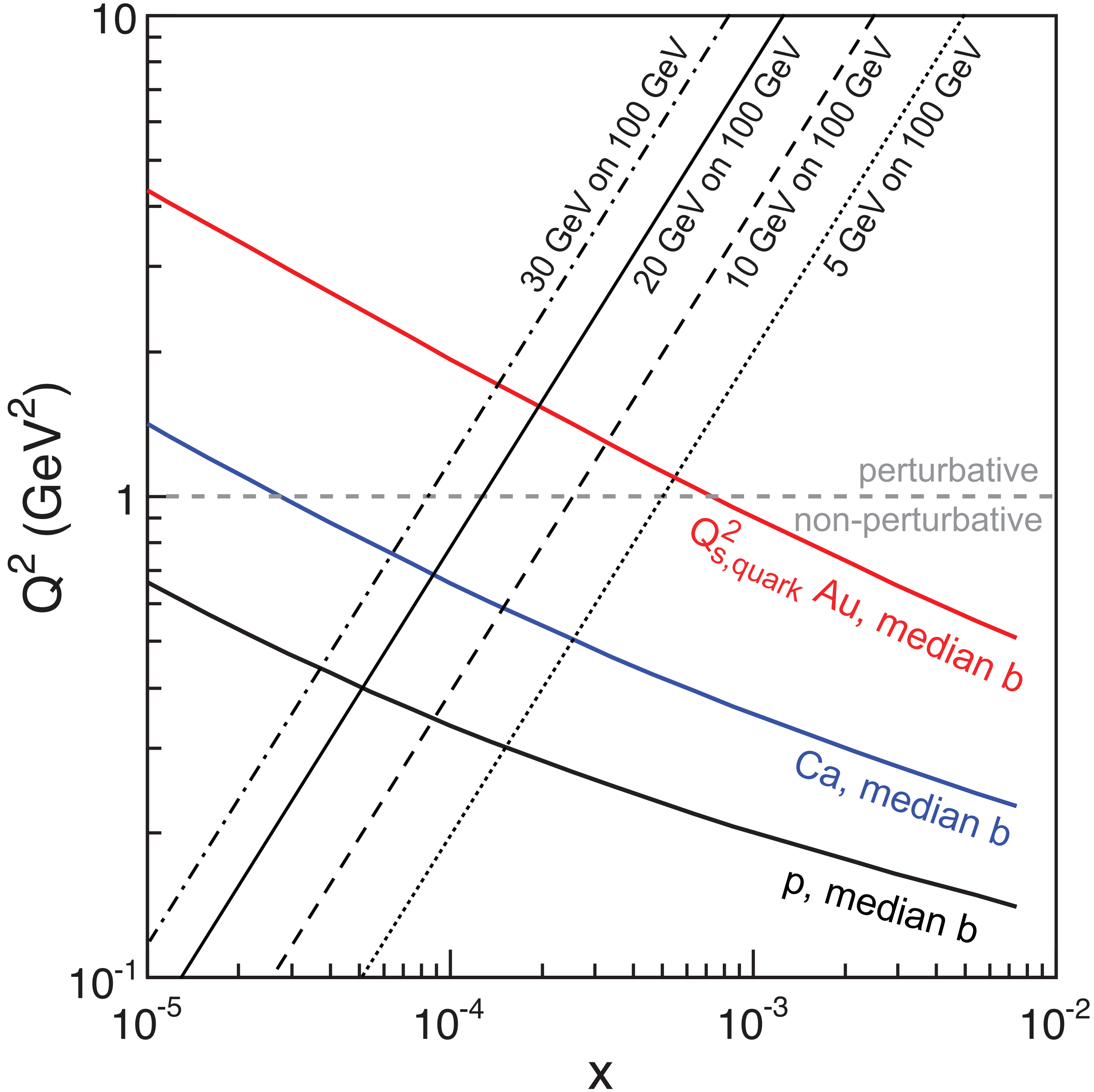


EIC



LHeC/FCC-eA

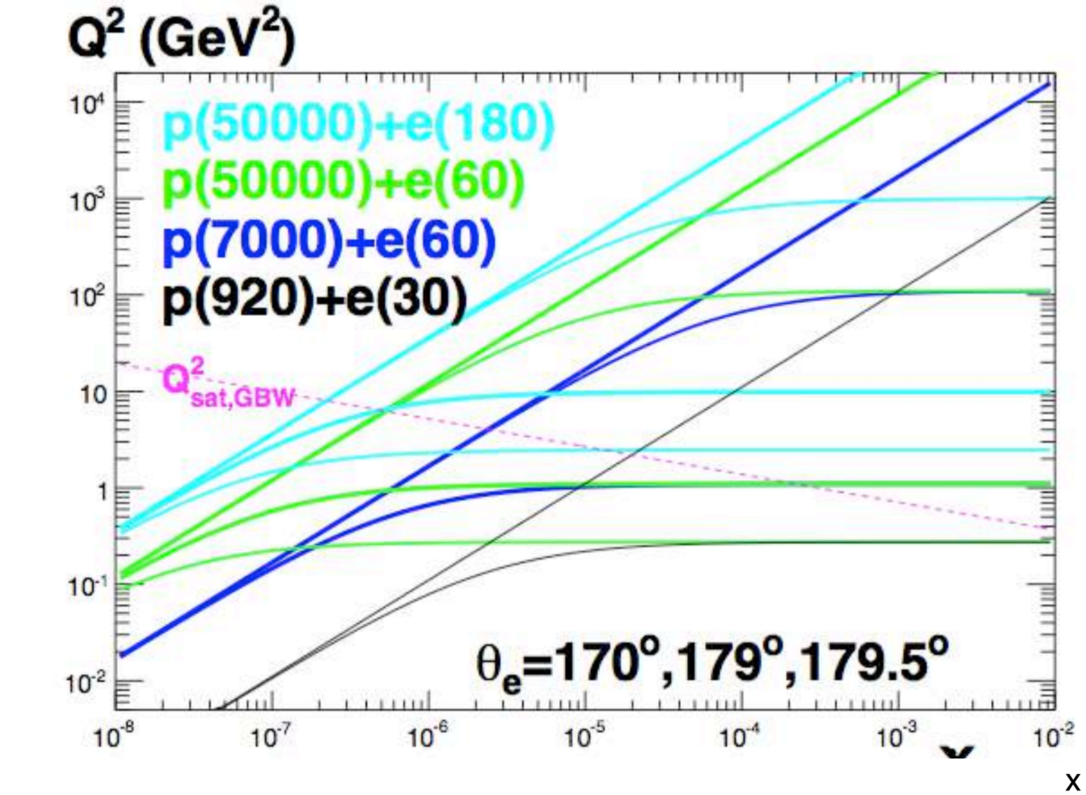
EIC sensitivity to saturation scale

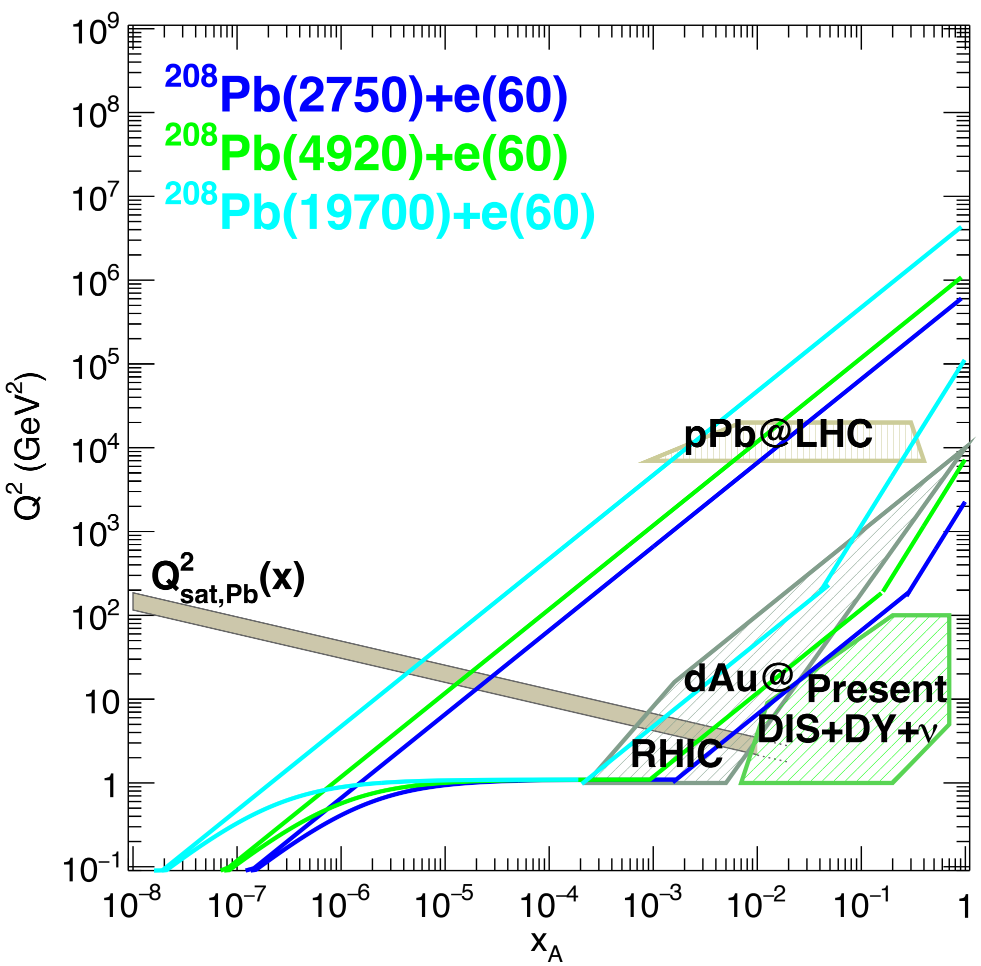


$$Q_s^2 \sim A^{1/3} Q_0^2 \left(\frac{1}{x}\right)^{\lambda}$$

EIC sensitive to perturbative saturation region in scattering with heavy nuclei.
Shown: median b-impact parameter.
Exclusive processes can be sensitive to different b.

LHeC/FCC-eh kinematics





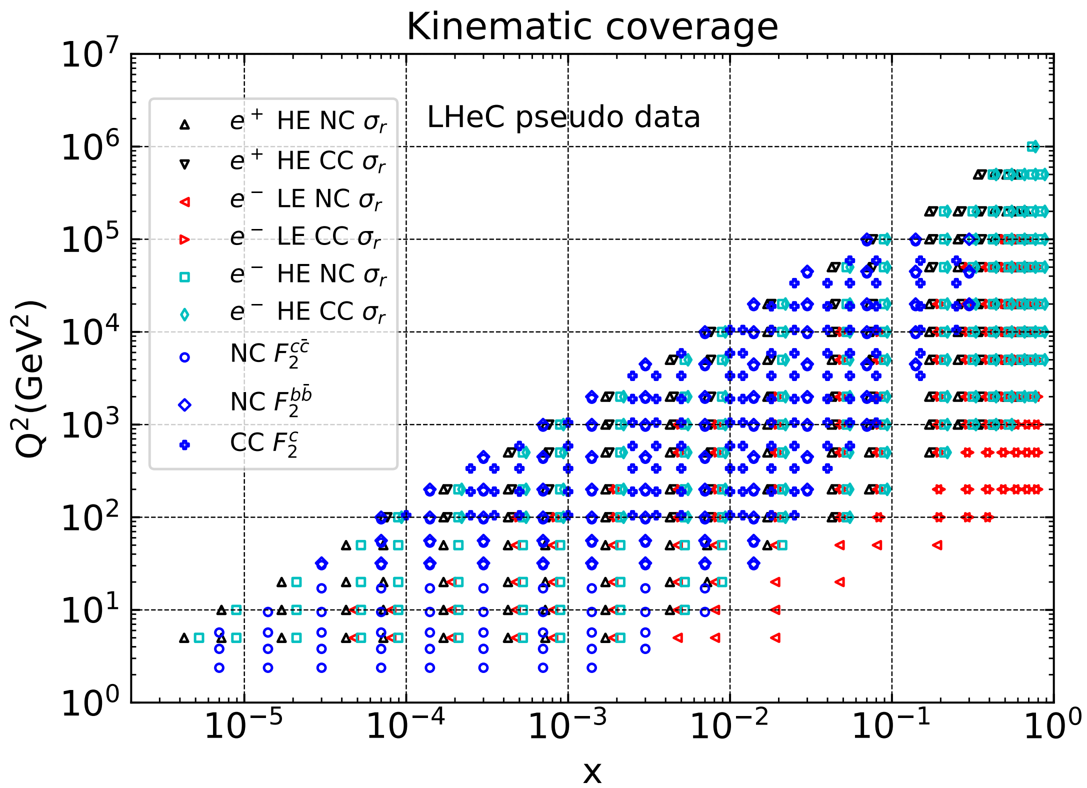
LHeC/FCC-eh: Small x machines. Obvious extension of the kinematic reach at FCC-(electron-hadron)

Higher electron energy reduces small x region unless detector acceptance is larger.

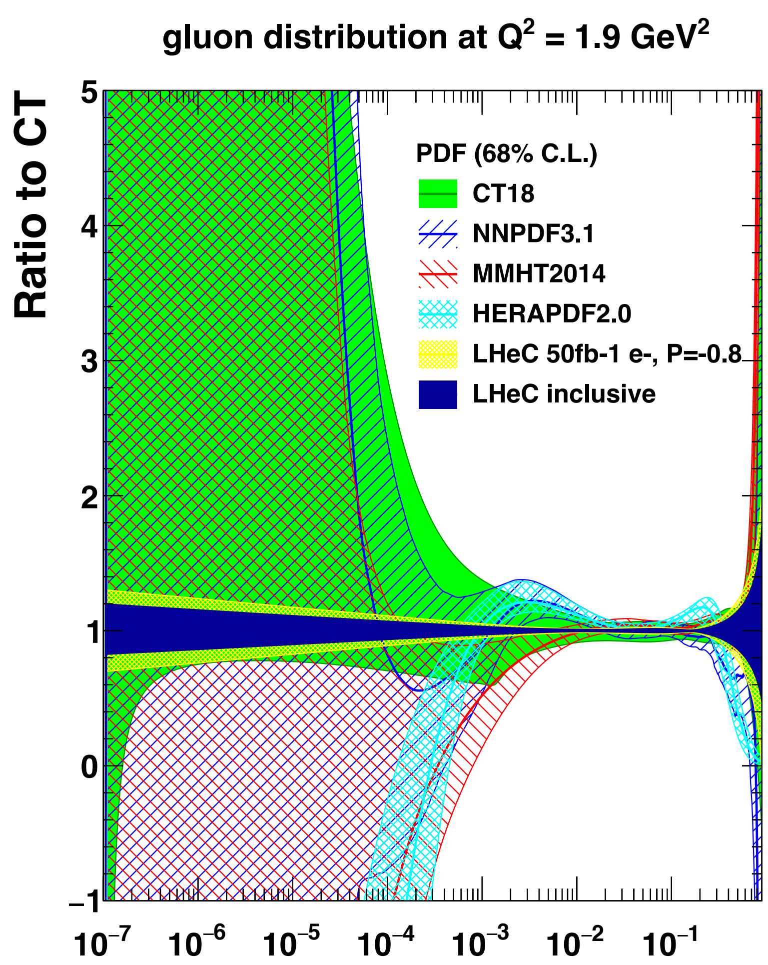
Similarly for eA mode: very small x domain in eA.

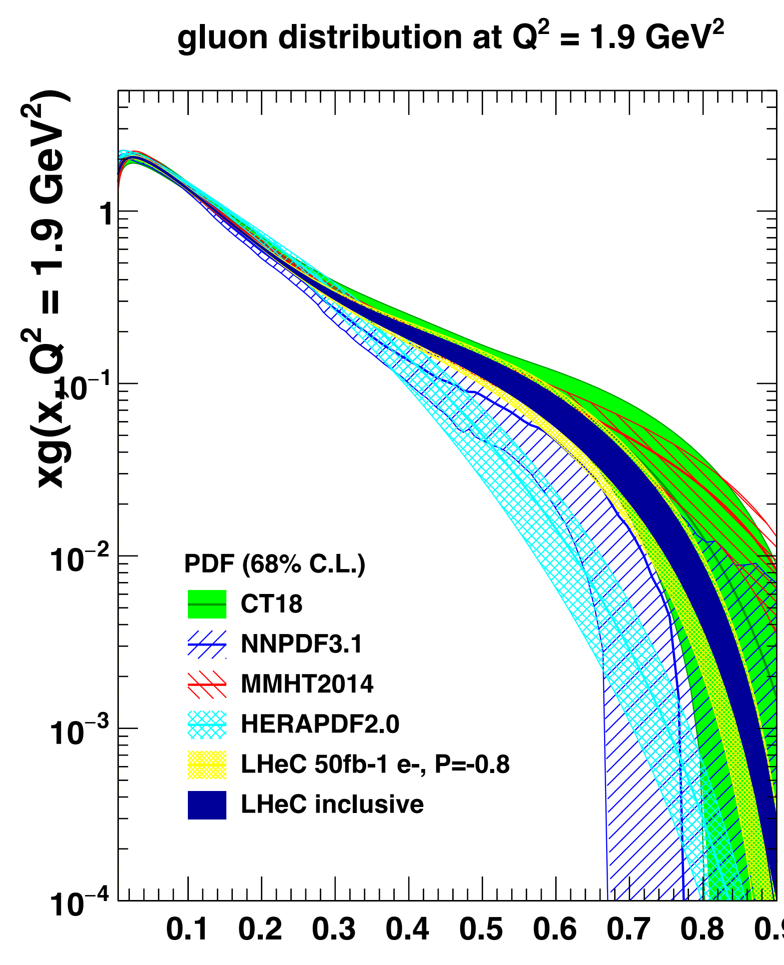
LHeC constraints on gluon

Pseudodata



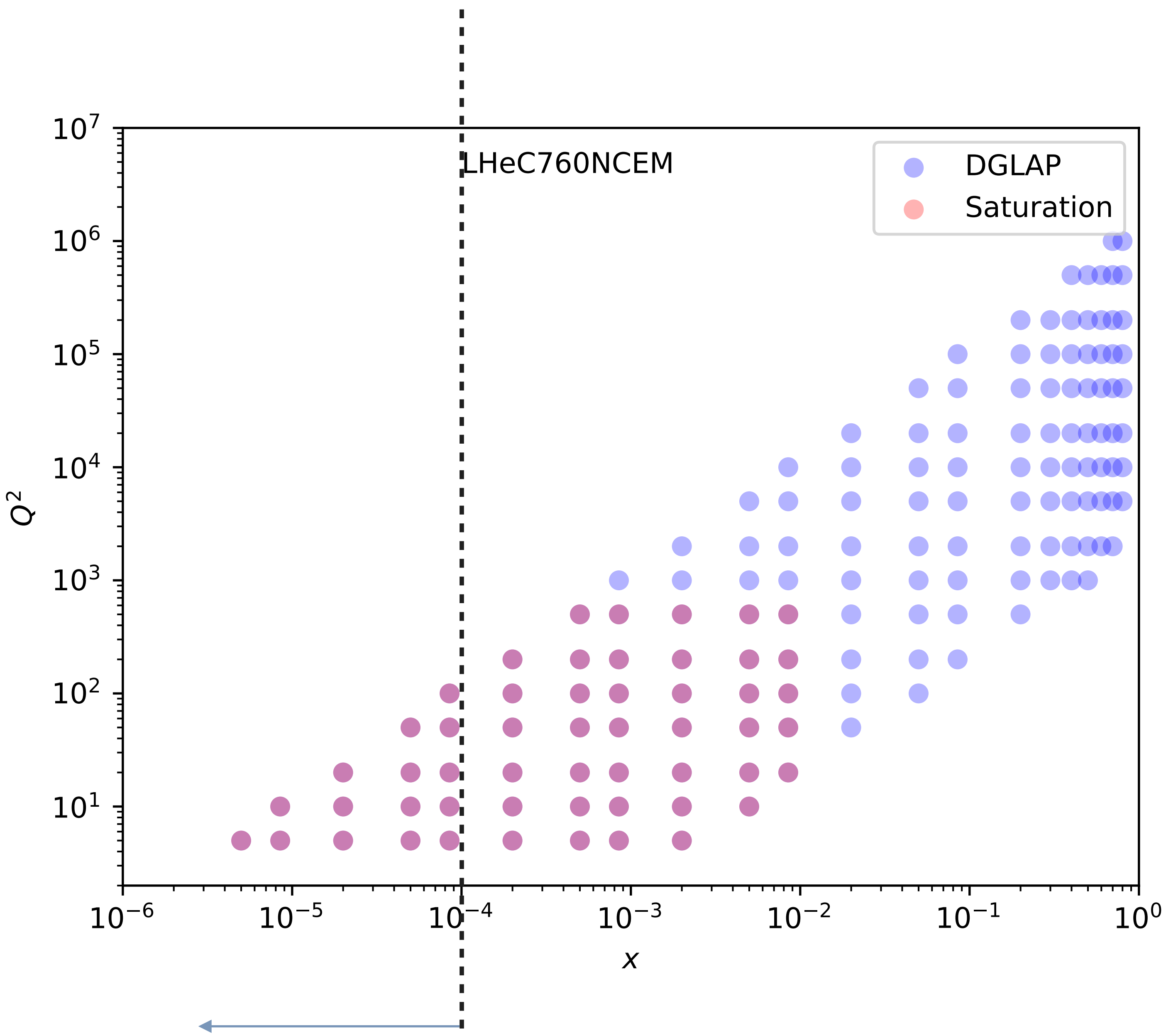
Constraints at both low and large x





Saturation: structure functions

Idea: generate pseudodata with/without saturation, fit with DGLAP and look for differences.



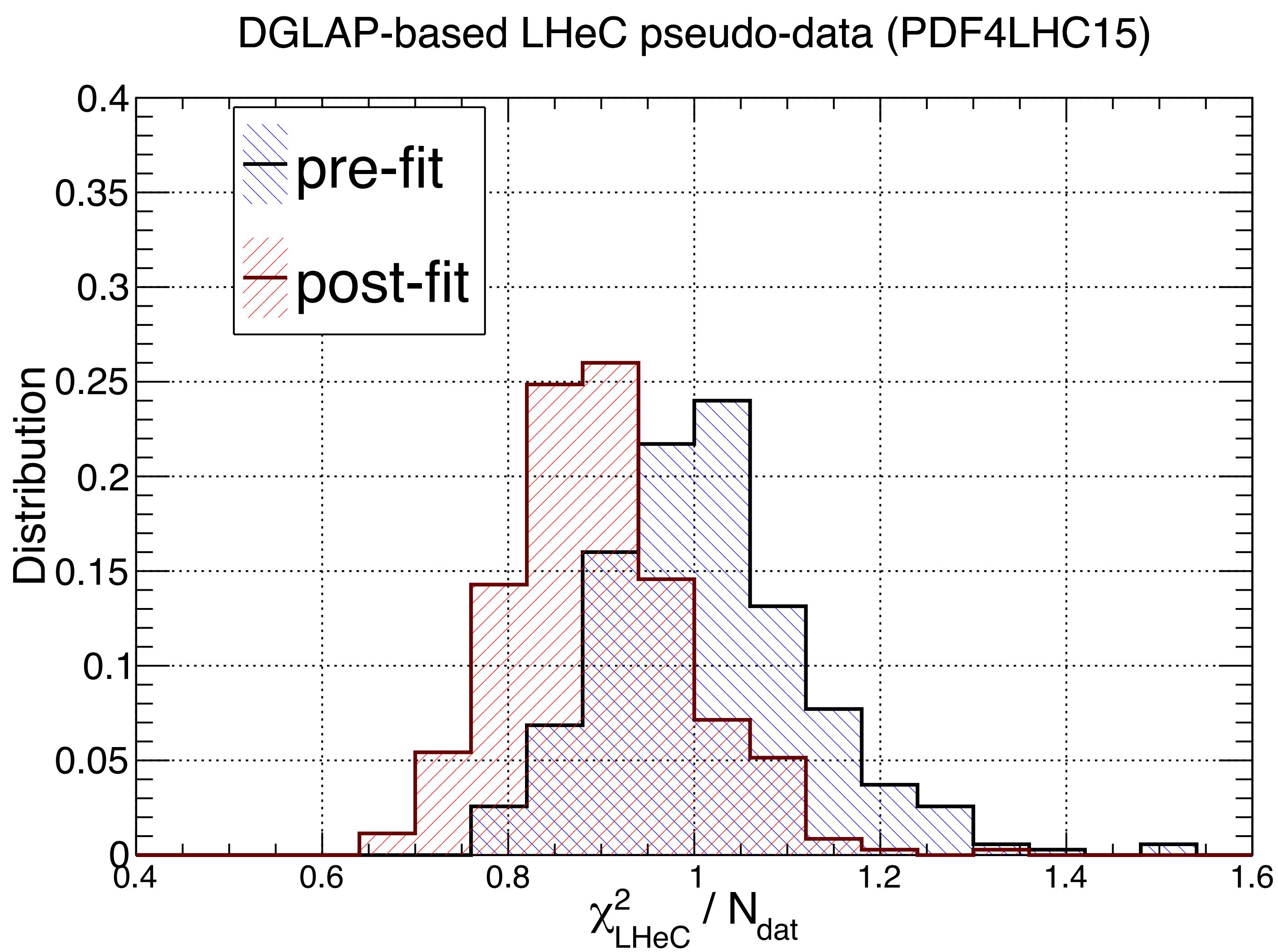
LHeC pseudodata: use two setups

- DGLAP only (PDF4LHC15)
- DGLAP for $x>10^{-4}$ and saturation model for $x<10^{-4}$ (Golec-Biernat, Sapeta)

Method : Abdul Khalek, Bailey, Gao, Harland-Lang, Rojo. Hessian profiling.

Generated 500 independent sets of LHeC NC pseudodata with random fluctuations determined by (projected) experimental uncertainties.

Saturation: structure functions



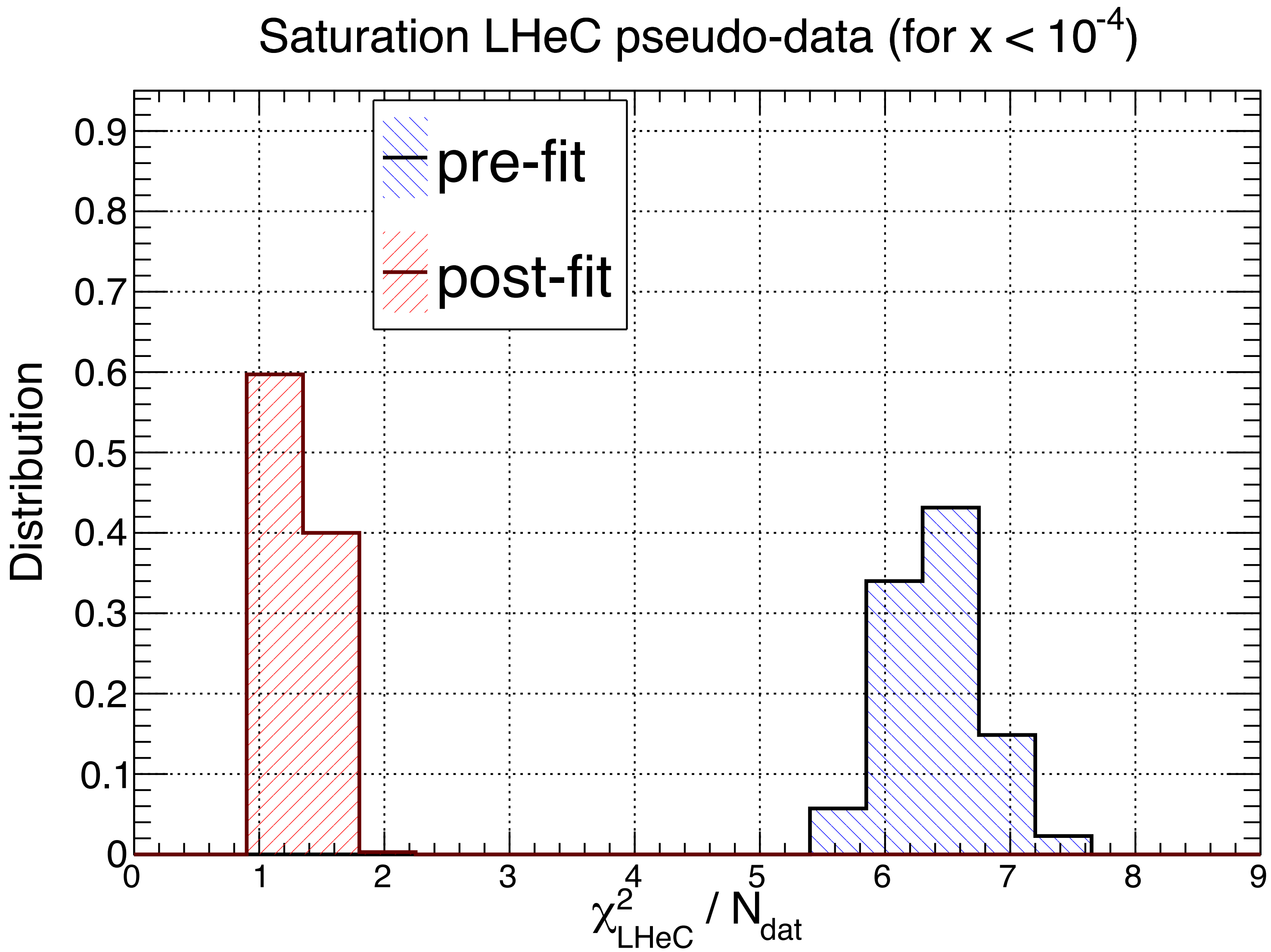
Distribution of pre-fit and post-fit values of

$$\chi^2/n_{\mathrm{dat}}$$

for 500 data sets.

Fit done with model used to generate pseudodata: very good agreement obviously…

Saturation: structure functions



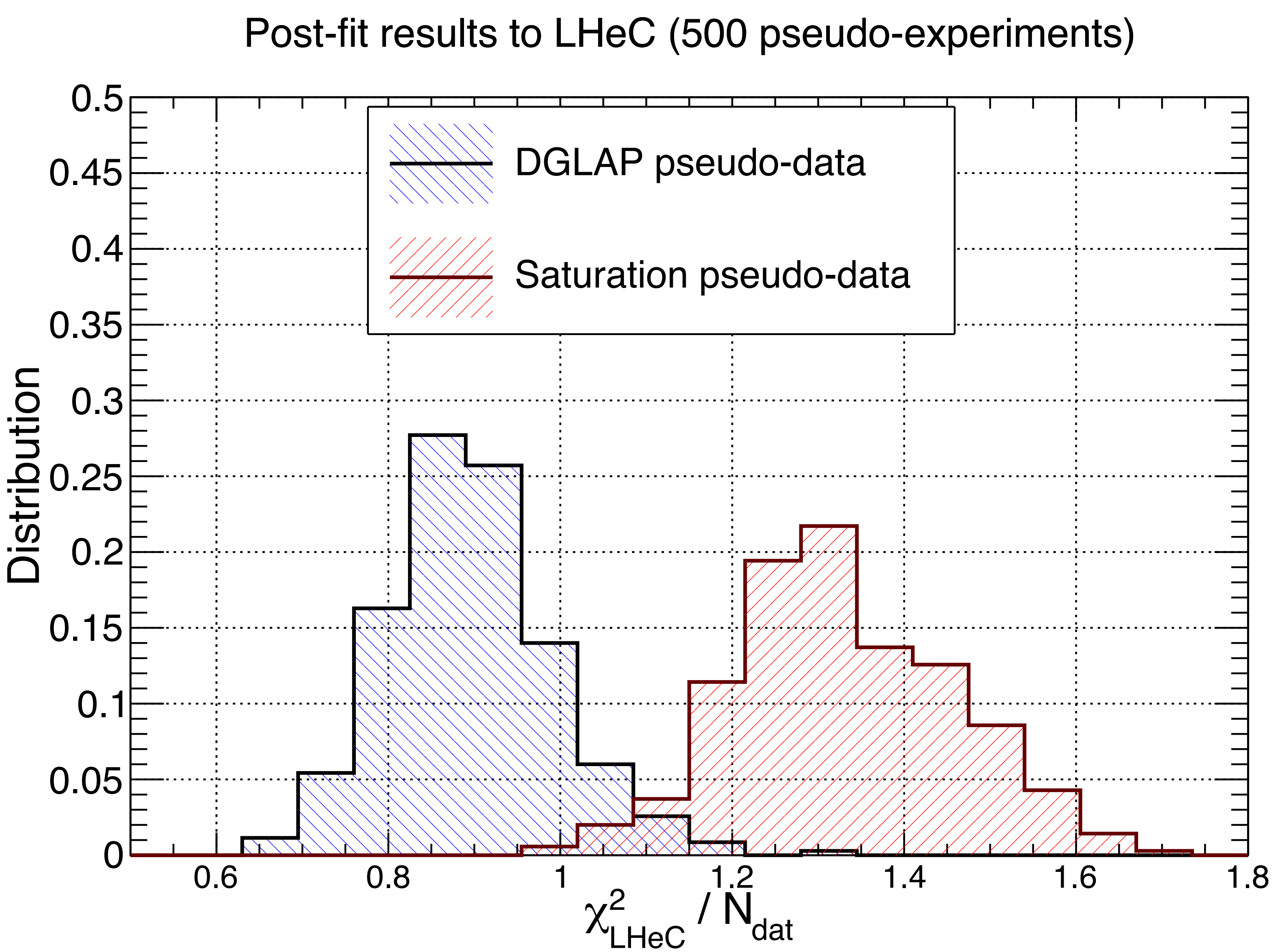
LHeC data with saturation:

Pre-fit distribution: mean around 6.5

Post-fit distribution: mean much lower 1.3
Seems like DGLAP can absorb saturation effects

But how much?

Saturation: structure functions



Zoom into post-fit distribution

Can still tell apart between DGLAP and saturation pseudodata

DGLAP cannot completely fit away saturation effects, if they are present at LHeC below $x<10^{-4}$

Comments: will strongly depend on model and range of x and Q where the modifications are present

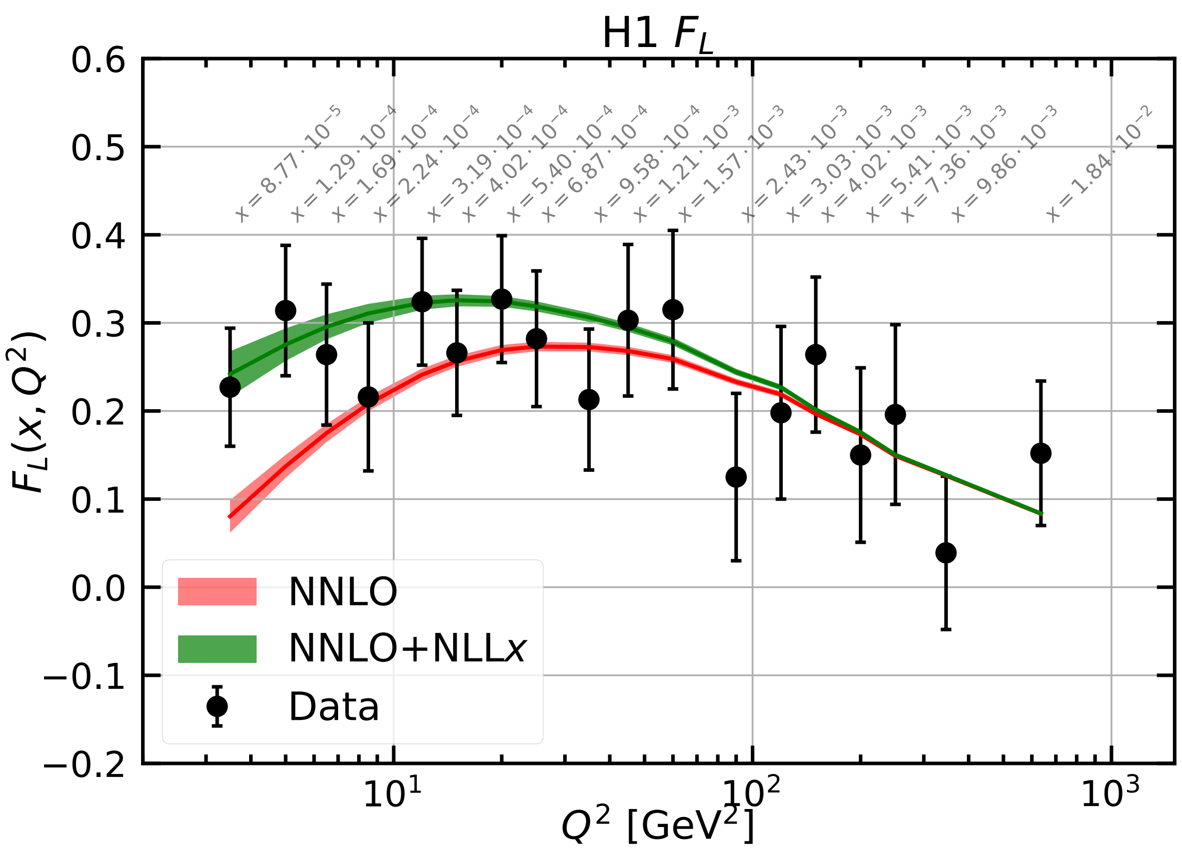
More pronounced at FCC

Can perform similar exercise with nuclear structure functions

Other observables: charm and longitudinal structure function

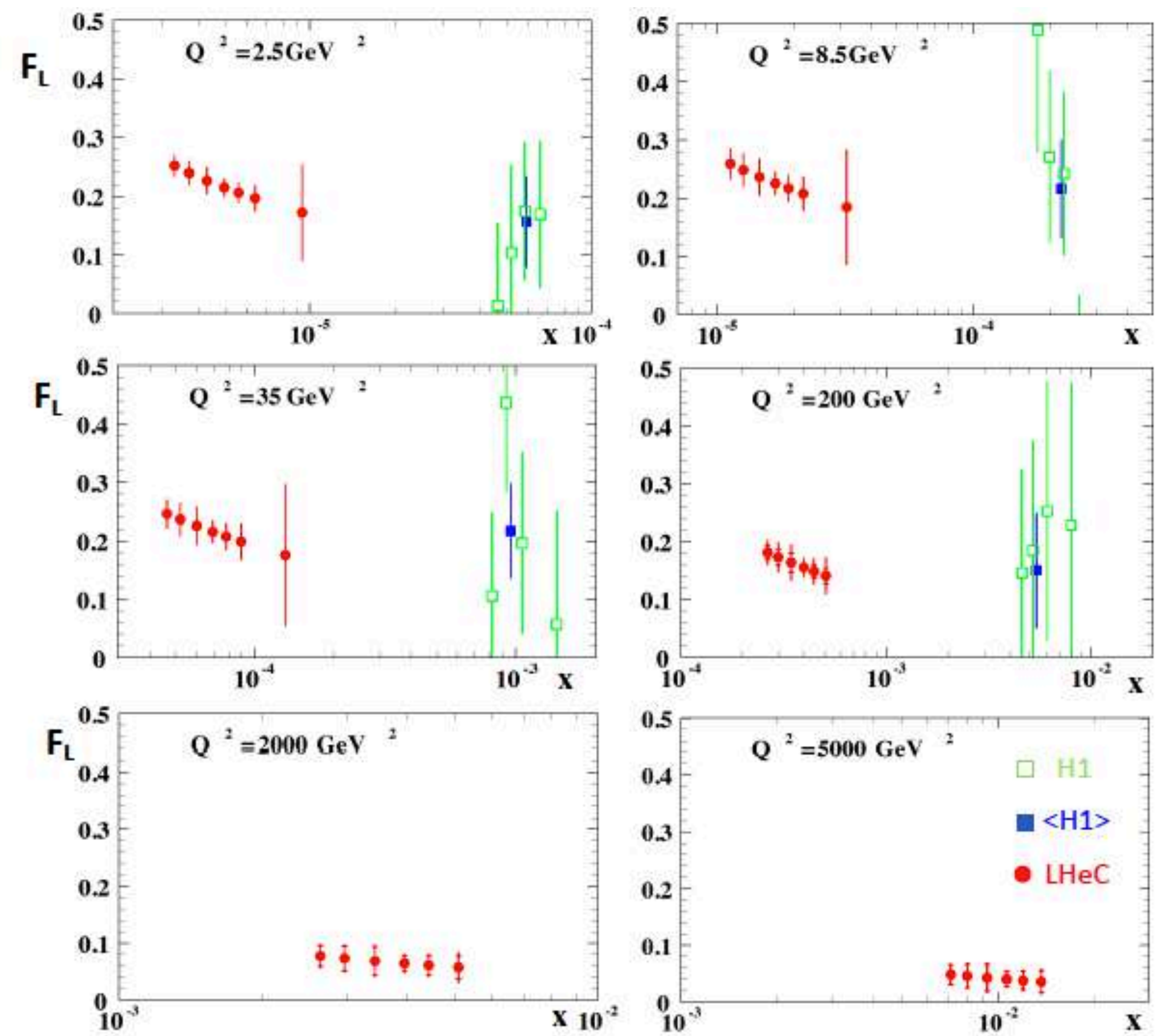
Longitudinal structure function

$$\frac{Q^4 x}{2\pi\alpha^2 Y_+}\cdot\frac{d^2\sigma}{dxdQ^2} = \sigma_r \simeq F_2(x,Q^2) - f(y)\cdot F_L(x,Q^2) = F_2\cdot\left(1-f(y)\frac{R}{1+R}\right) \qquad y = Q^2/sx$$



Longitudinal structure function: important constraint on the gluon

Challenging experimentally: vary energy, F_L small, systematics



E_p=7 TeV, E_e=60,30,20 GeV

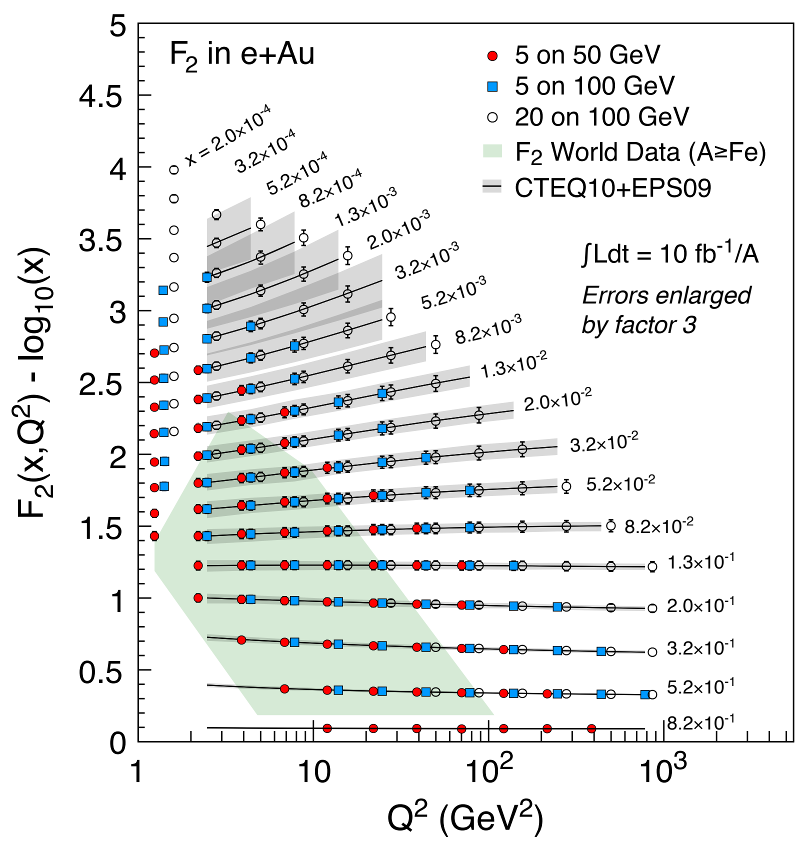
Luminosity: 10, 1 , 1 fb^{-1}

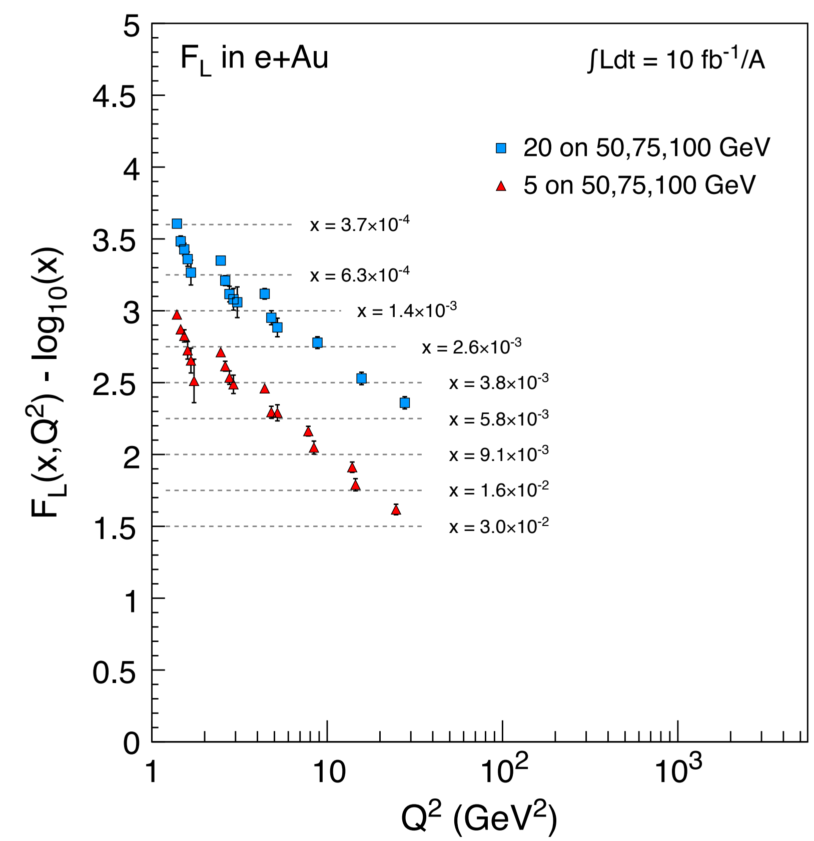
Correlated and uncorrelated systematics

Structure functions at EIC

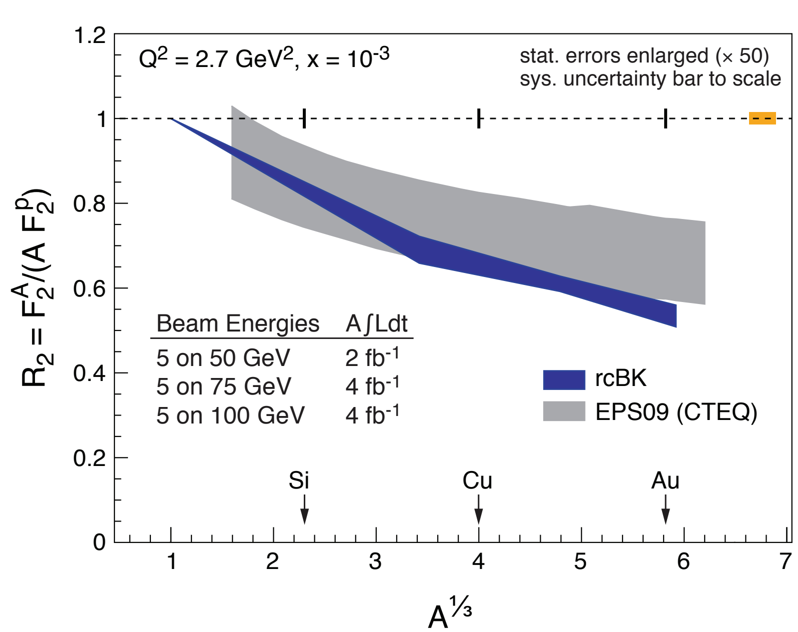
EIC: structure function simulations in eA

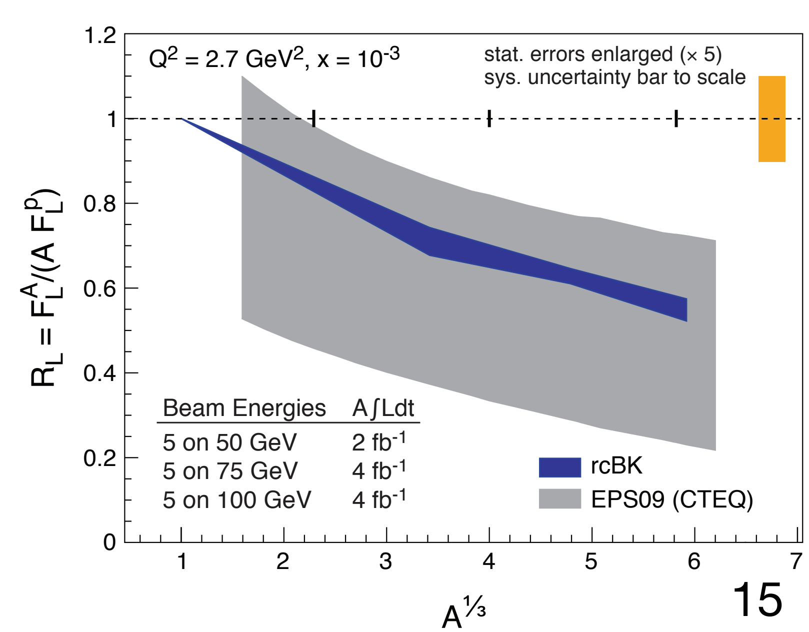
Pseudodata simulated with EPS09, very high precision data for eA



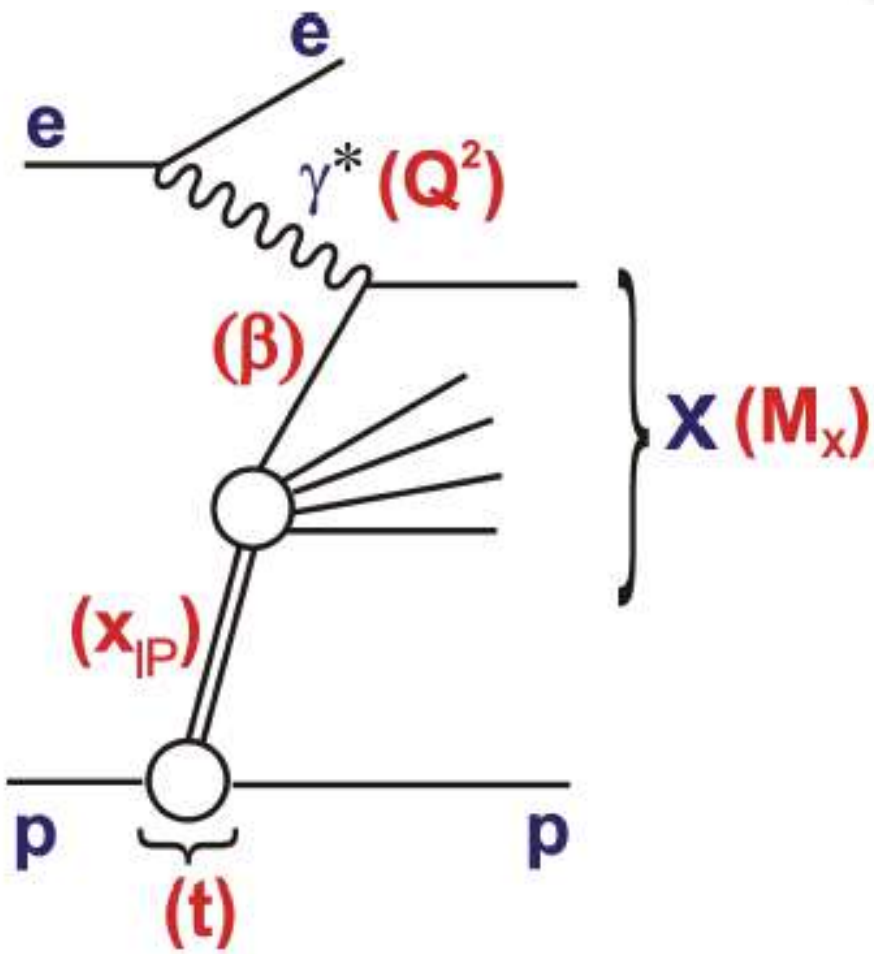


- Nonlinear evolution has smaller range of uncertainty. Robustness of the solution to nonlinear equation.
- Large dependence on the initial conditions for the linear evolution leads to large uncertainty.





Diffraction



$$\xi \equiv x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$

momentum fraction of the Pomeron w.r.t hadron

$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$

momentum fraction of parton w.r.t Pomeron

$$x_{Bj} = x_{IP}\beta$$

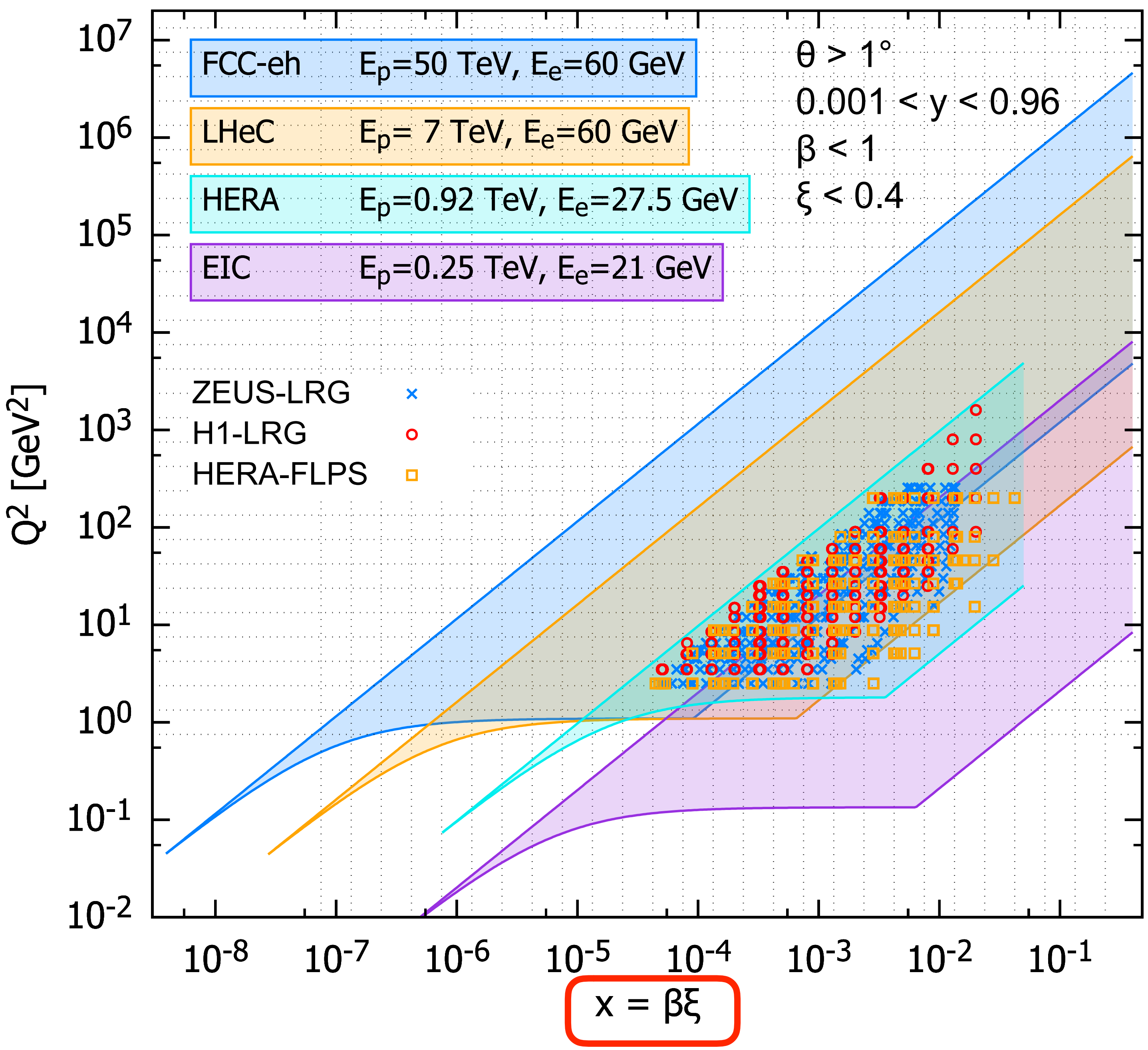
Theoretical description of such process is in terms color-less exchange : the Pomeron.

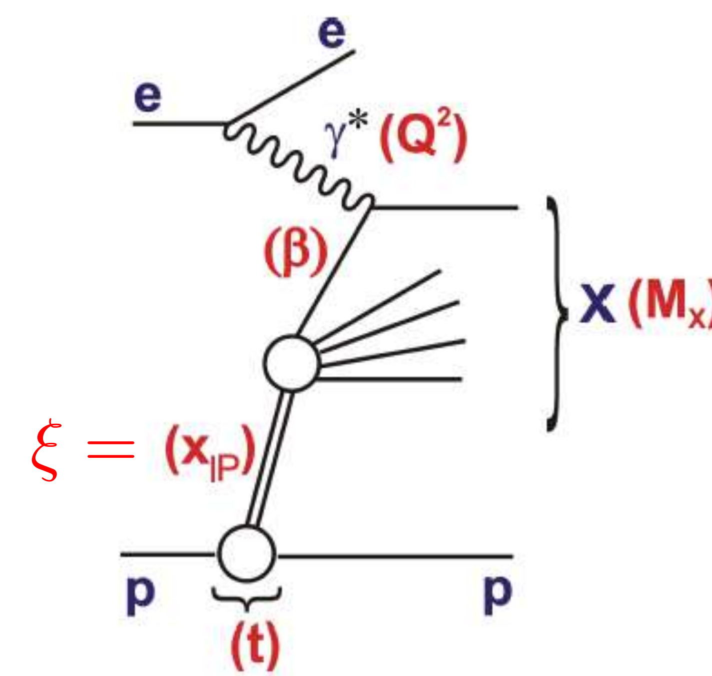
For large scales the QCD factorization was shown.

What can be done at an EIC/LHeC/FCC-eh?

- Tests of factorization of diffractive parton distributions (ep and eA).
- Sensitivity and relation to saturation physics (smaller scales involved).
- Study relation between diffraction in ep and shadowing in eA.

Phase space: LHeC, FCC-eh,EIC





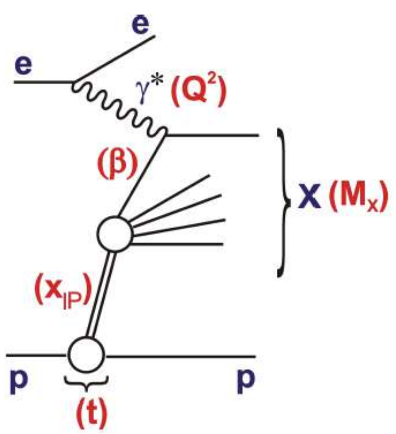
$E_e = 60$ GeV

LHeC
- $E_p = 7$ TeV vs. HERA
  - $x_{\min}$ down by factor ~20
  - $Q^2_{\max}$ up by factor ~100

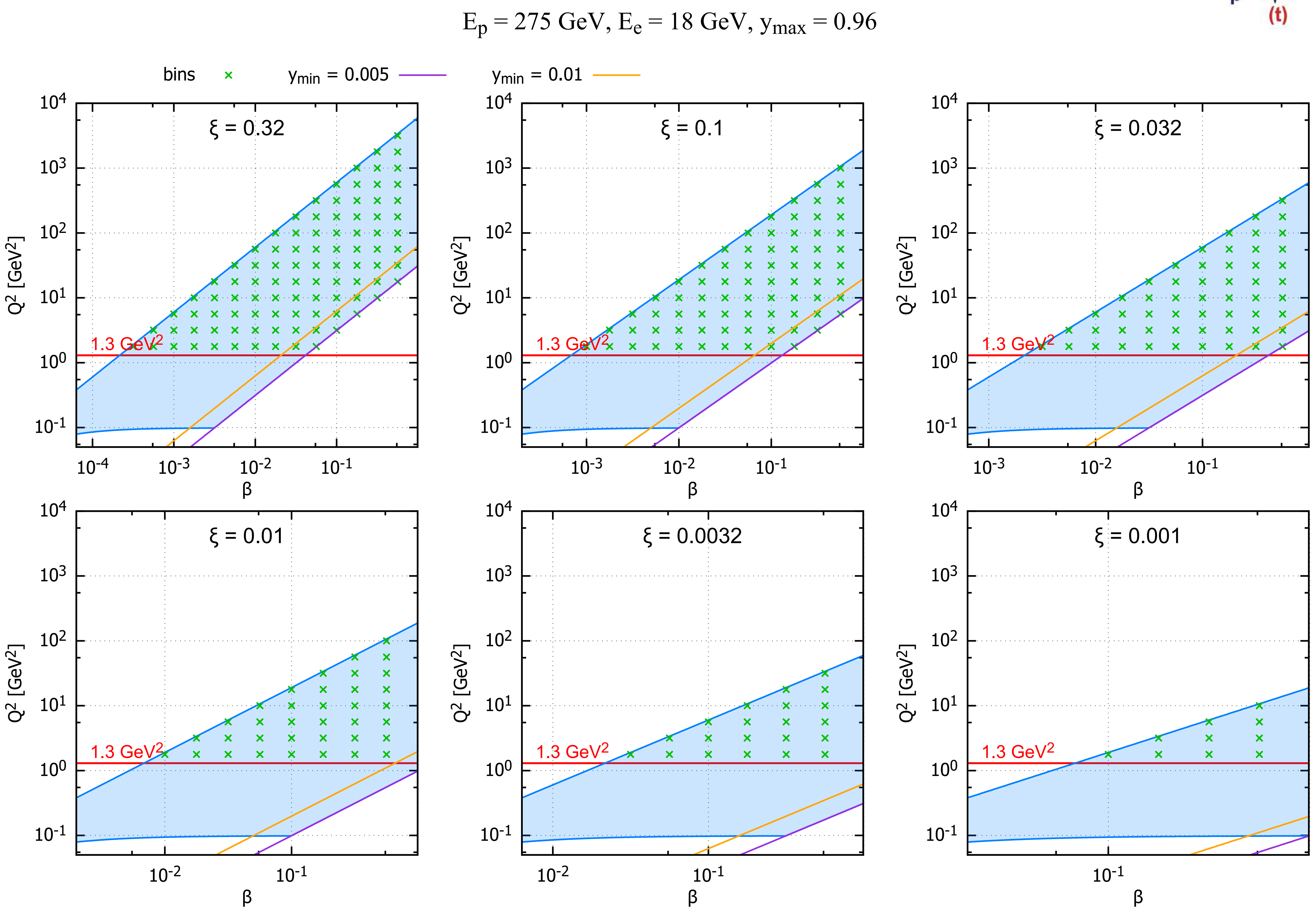
FCC
- $E_p = 50$ TeV vs. 7 TeV
  - $x_{\min}$ down by factor ~10
  - $Q^2_{\max}$ up by factor ~10

For the EIC: better than HERA coverage of the large x region

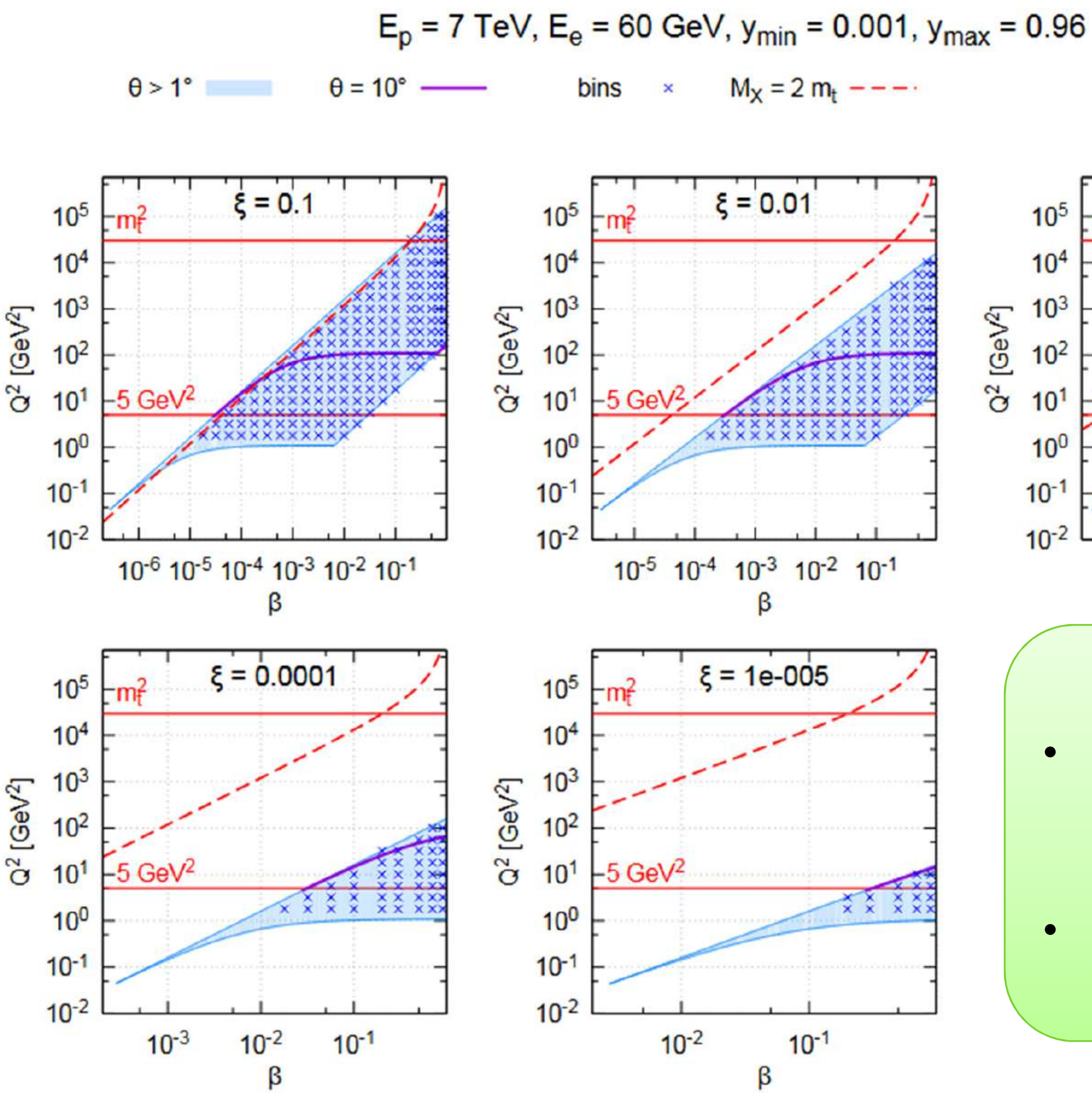
EIC phase space: (β,Q^2) fixed ξ



$$\xi = x_{IP}$$



LHeC phase space: (β, Q^2) fixed ξ

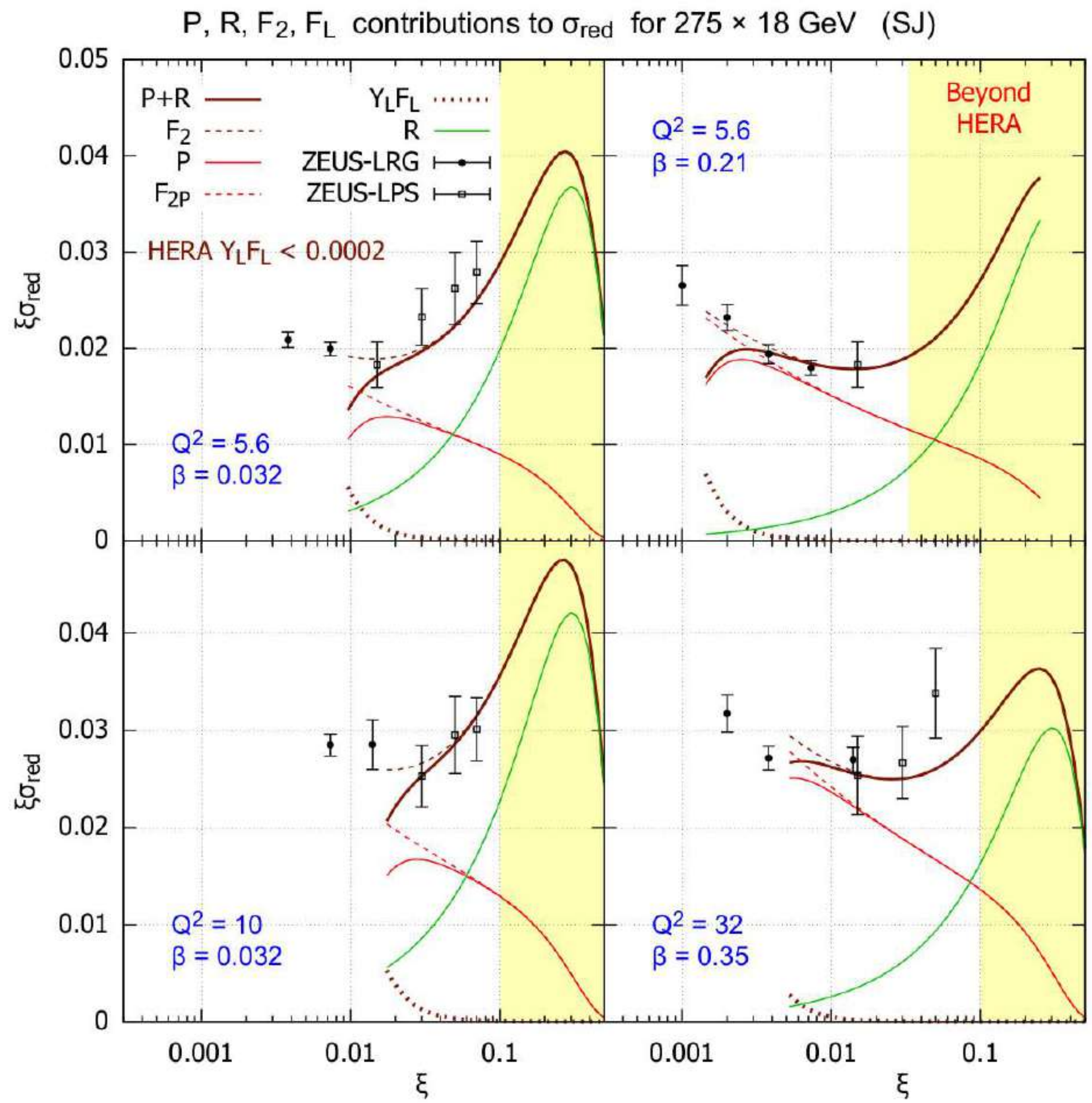


 # bins for $\xi < 0.15$

- no top
  - 1589 for $Q^2 > 1.3\ \mathrm{GeV}^2$
  - 1229 for $Q^2 > 5\ \mathrm{GeV}^2$
- with top quark
  - 17 bins more

EIC: Pomeron/Reggeon decomposition

Pomeron, Reggeon, F_2, F_L components of σ_{red}



- ❑ $\mathbb{R}$ contribution dominates at high ξ
- ❑ Significant F_{L} component

$$\sigma_{\mathrm{red}} = F_2 \;\; - Y_{\mathrm{L}}(y)\, F_{\mathrm{L}}$$

$$Y_{\mathrm{L}}(y) = \frac{y^2}{1+(1-y)^2}$$

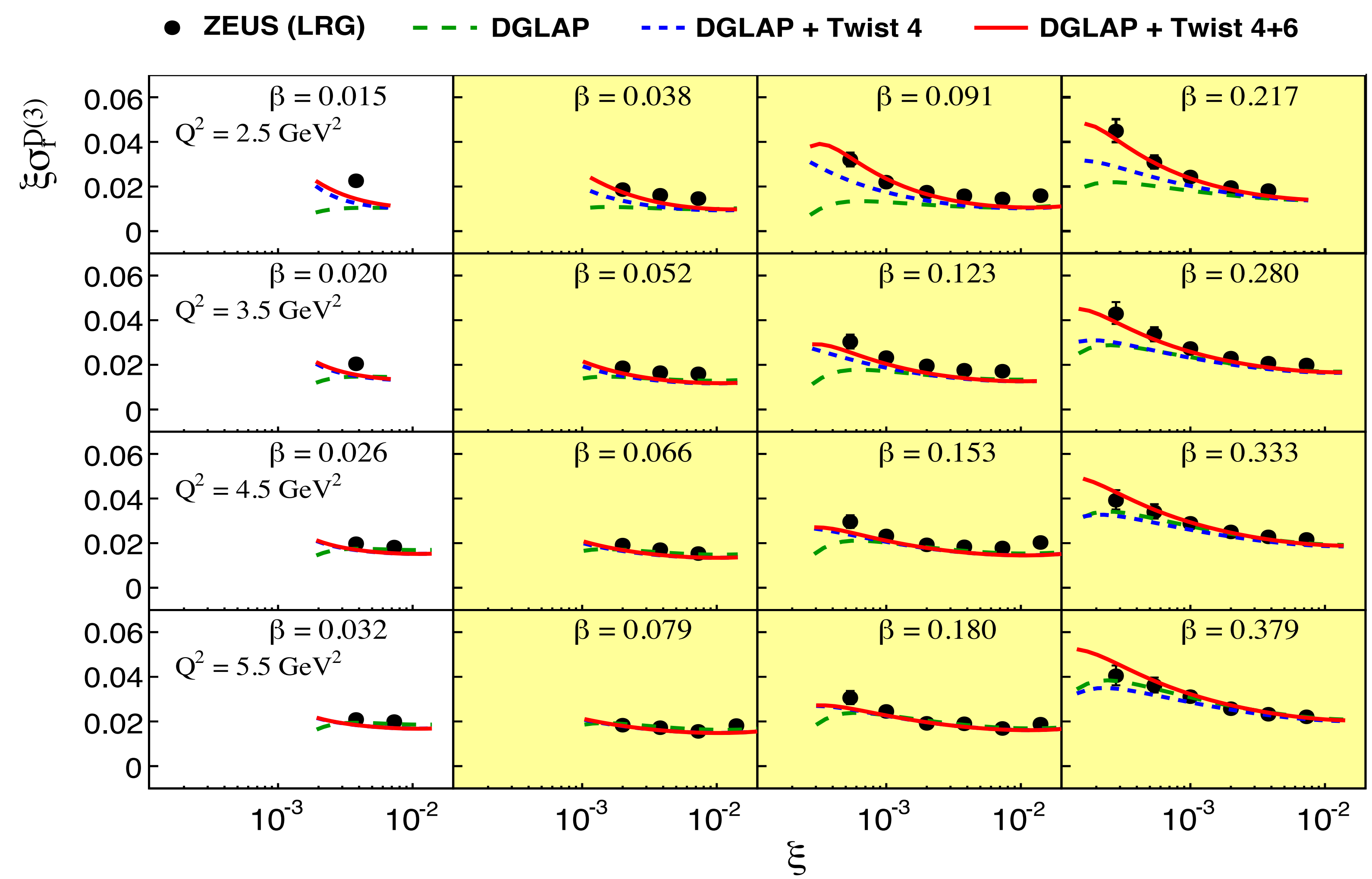
At fixed (x, Q^2),
$Y_{\mathrm{L}}(y)$ scales stronger than $\sim 1/s^2$,
e.g. $Y_{\mathrm{L}}(0.9/5)/Y_{\mathrm{L}}(0.9) = 0.024$

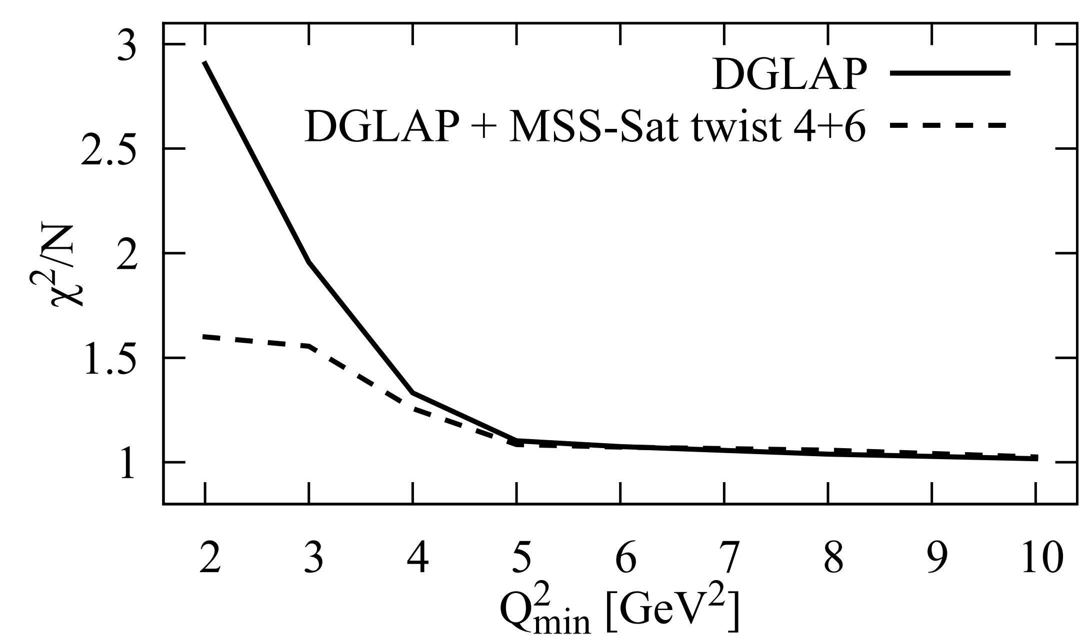
$x_L \lesssim 0.6$ required for the determination of subleading "Reggeon" term.
Some intermediate beam energy settings needed for F_{L} measurements.

Higher twists in diffraction

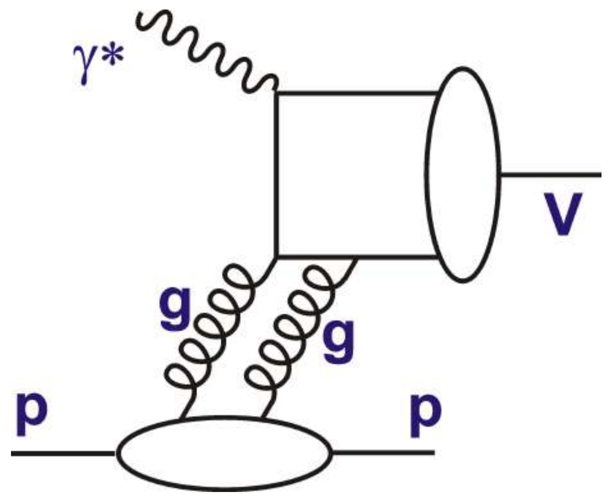
Motyka, Sadzikowski, Slominski

- Diffractive data at HERA cannot be described by DGLAP at low Q^2
- Higher twists 4 and 6 evaluated from the dipole saturation model
- Improves the quality of the fit significantly
- Largest effect at low Q^2 and small ξ
- Indication for large higher twists
- Questions for EIC/LHeC/FCC-eh: how would that change with different A and energy?

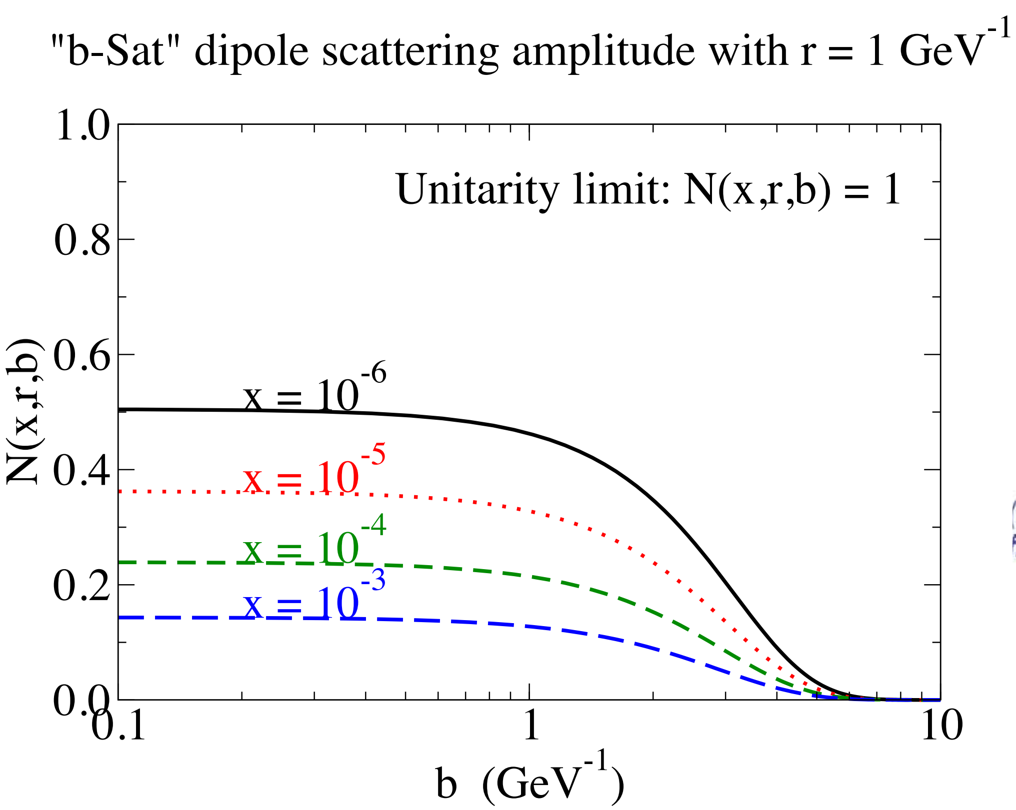


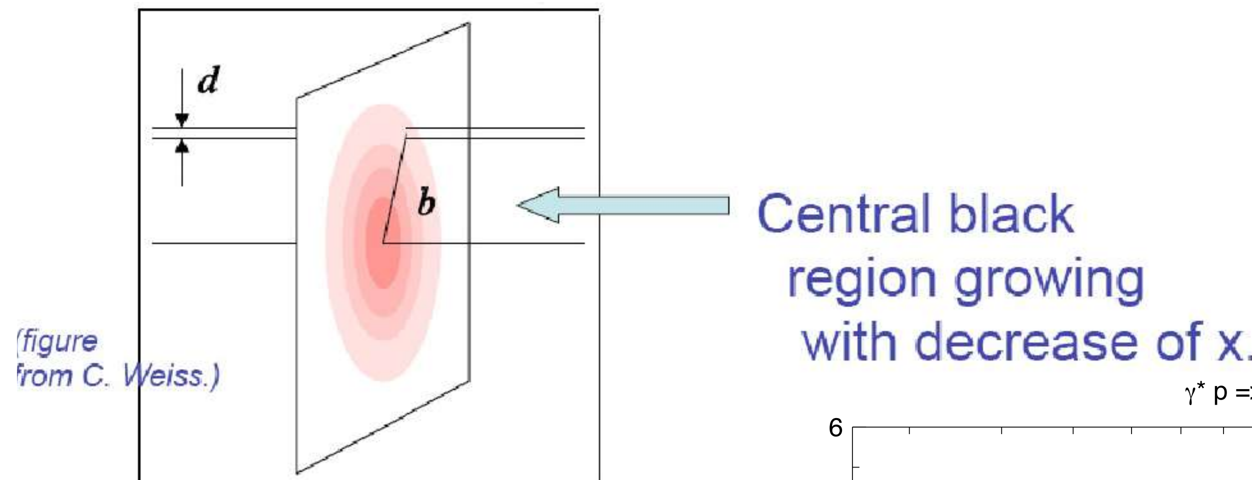


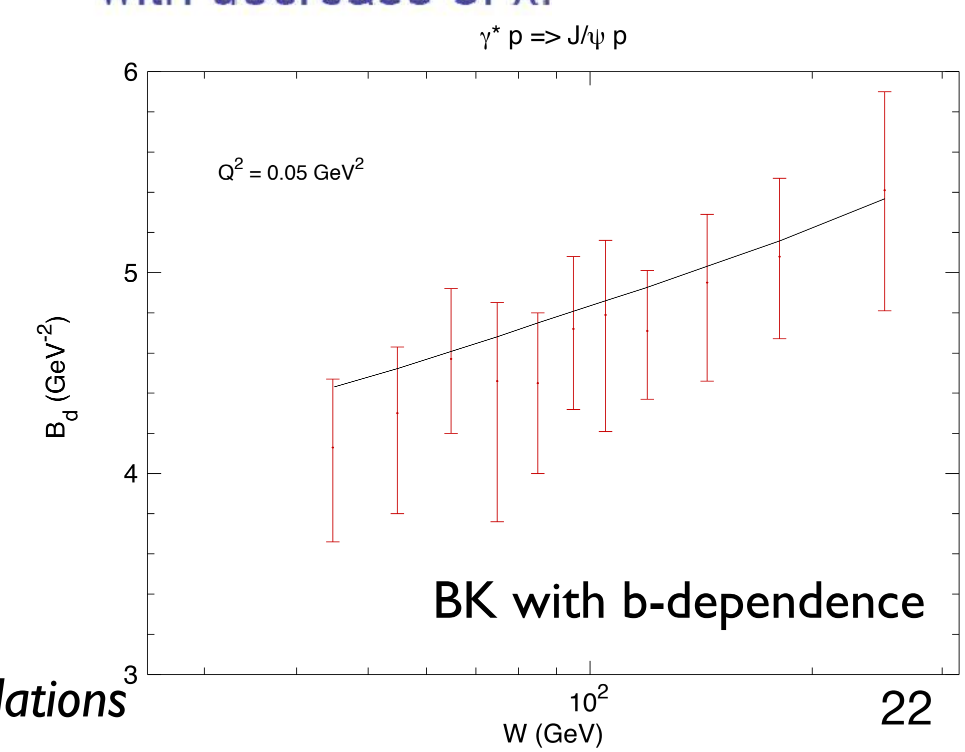
Exclusive diffraction



- Exclusive diffractive production of VM : extracting the dipole amplitude and GPDs
- Suitable process for estimating the ‘blackness’ of the interaction.
- t-dependence : impact parameter profile







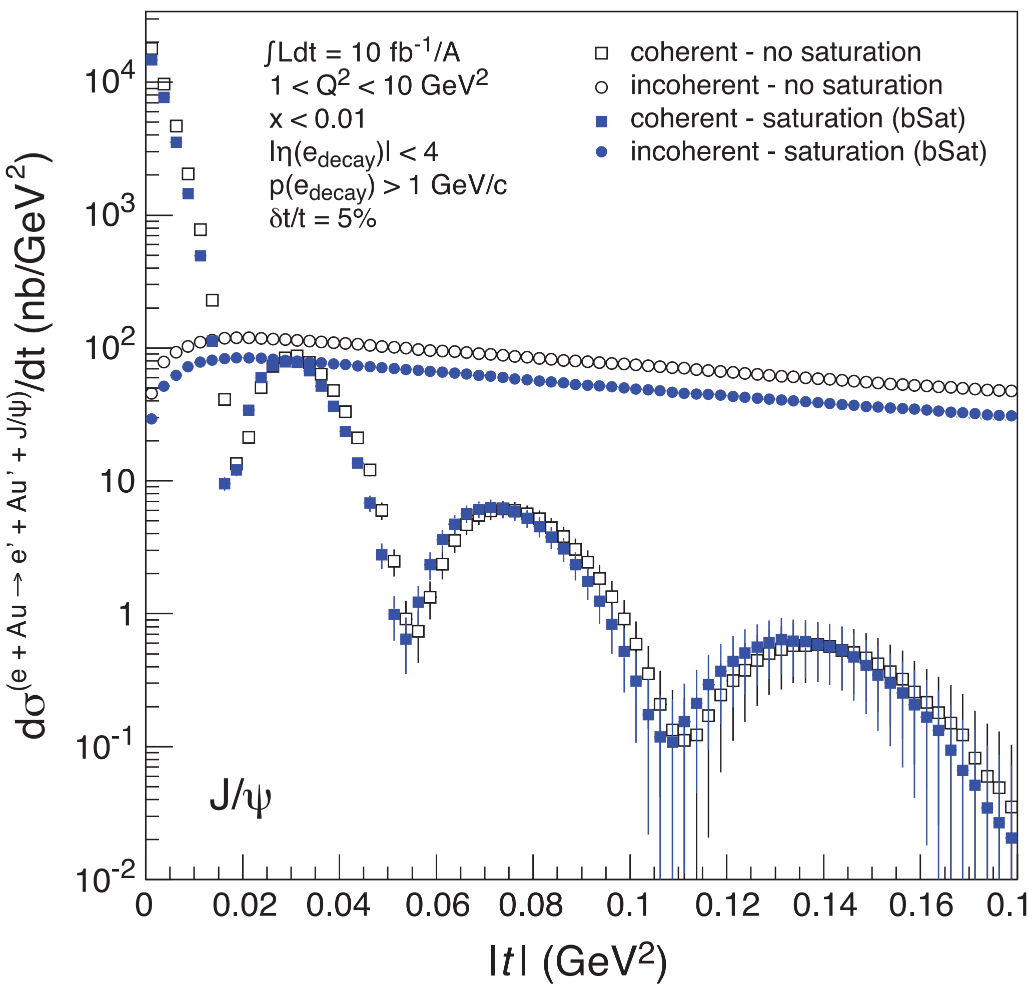
Large momentum transfer t probes small impact parameter where the density of interaction region is most dense.

HERA data compared with nonlinear evolution simulations

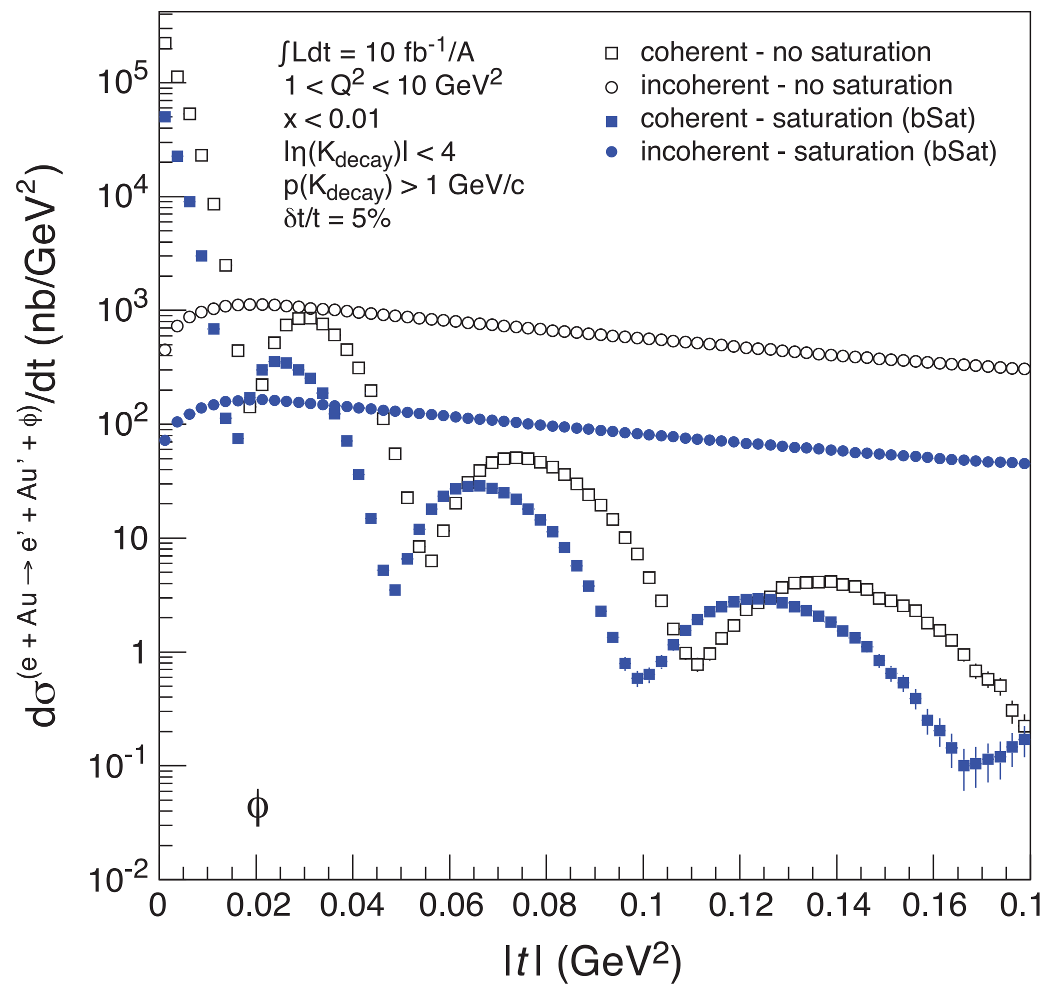
Exclusive diffraction on nuclei

Possibility of using the same principle to learn about the gluon distribution in the nucleus.
Possible nuclear resonances at small t?

EIC: J/Ψ



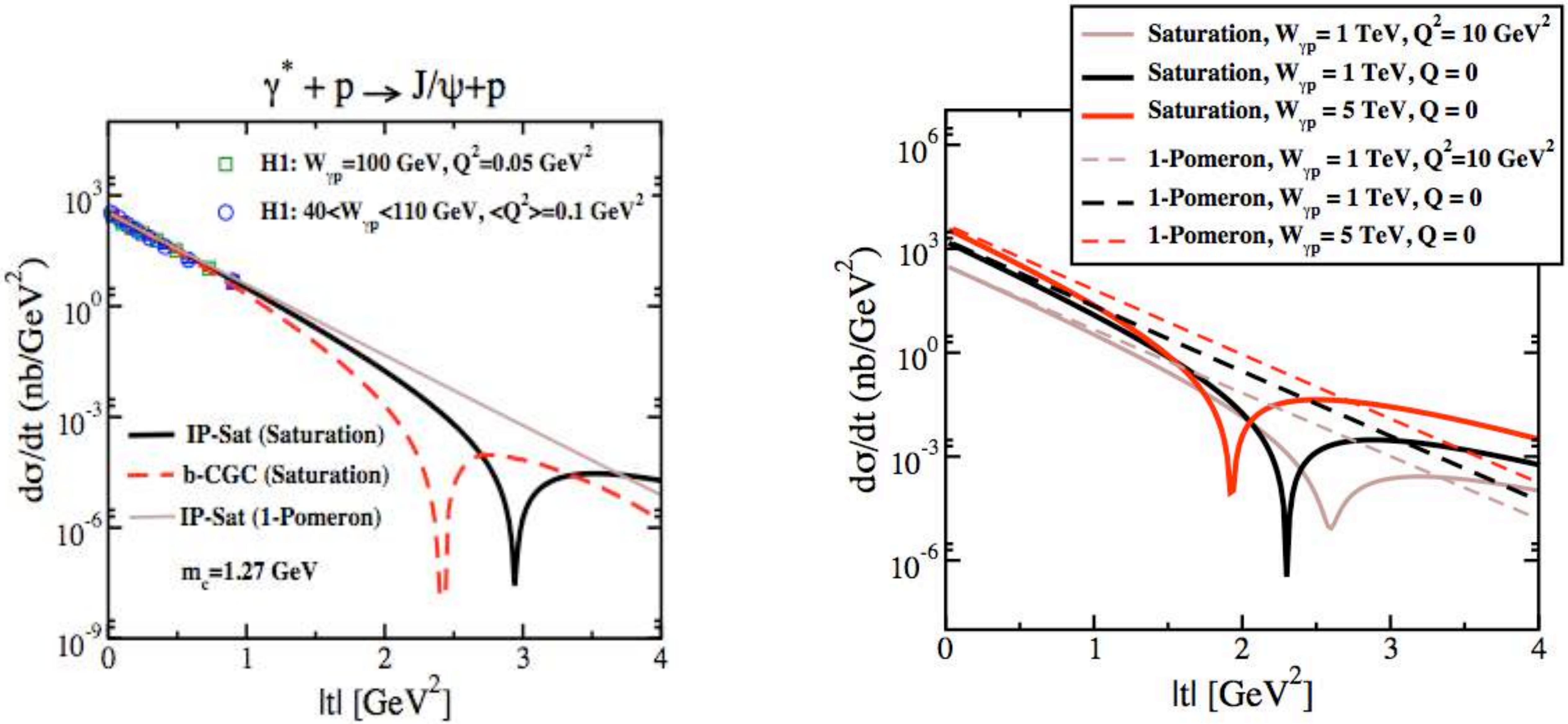
EIC: Φ



t-dependence: for nuclei dips. Position depends on model (sat no sat)
Challenges: need to distinguish between coherent and incoherent diffraction. Need dedicated instrumentation, zero degree calorimeter.

Dips in t-profile for VM production

Armesto-Rezaeian



- t-dependence is a Fourier transform of the impact parameter profile
- characteristic dips as a feature of saturation
- position of dips depends on energy and scale
- within the LHeC sensitive t-range

Summary

- Novel QCD phenomena expected at high parton density.
- Can reach this regime either by increasing A or decreasing x.
- Proton and nuclear structure functions and PDFs can provide the test of these effects. Quantifying possible deviations from DGLAP evolution.
- F_L measurement would greatly improve the prospects of constraining higher twists and saturation. Importance of heavy quark measurements.
- Diffraction, both inclusive and exclusive offers unique window to saturation physics. Relation between diffraction and shadowing. Inclusive data at HERA point to higher twists in this process. EIC can disentangle Reggeon/Pomeron contribution.
- Exclusive diffraction on of the best ways to perform the nucleon/nucleus tomography. VM elastic diffractive production; dips in t as a sign of parton saturation.
- Incoherent diffraction as a probe of the fluctuation of the gluon density.
- Azimuthal (de)correlations, sensitivity to the intrinsic transverse momentum of the gluon in the low x (or high A) regime. Ridge, collective phenomena at ep/eA?
- Importance of low x dynamics to ultrahigh cosmic ray and neutrino physics (Auger, ICECUBE)